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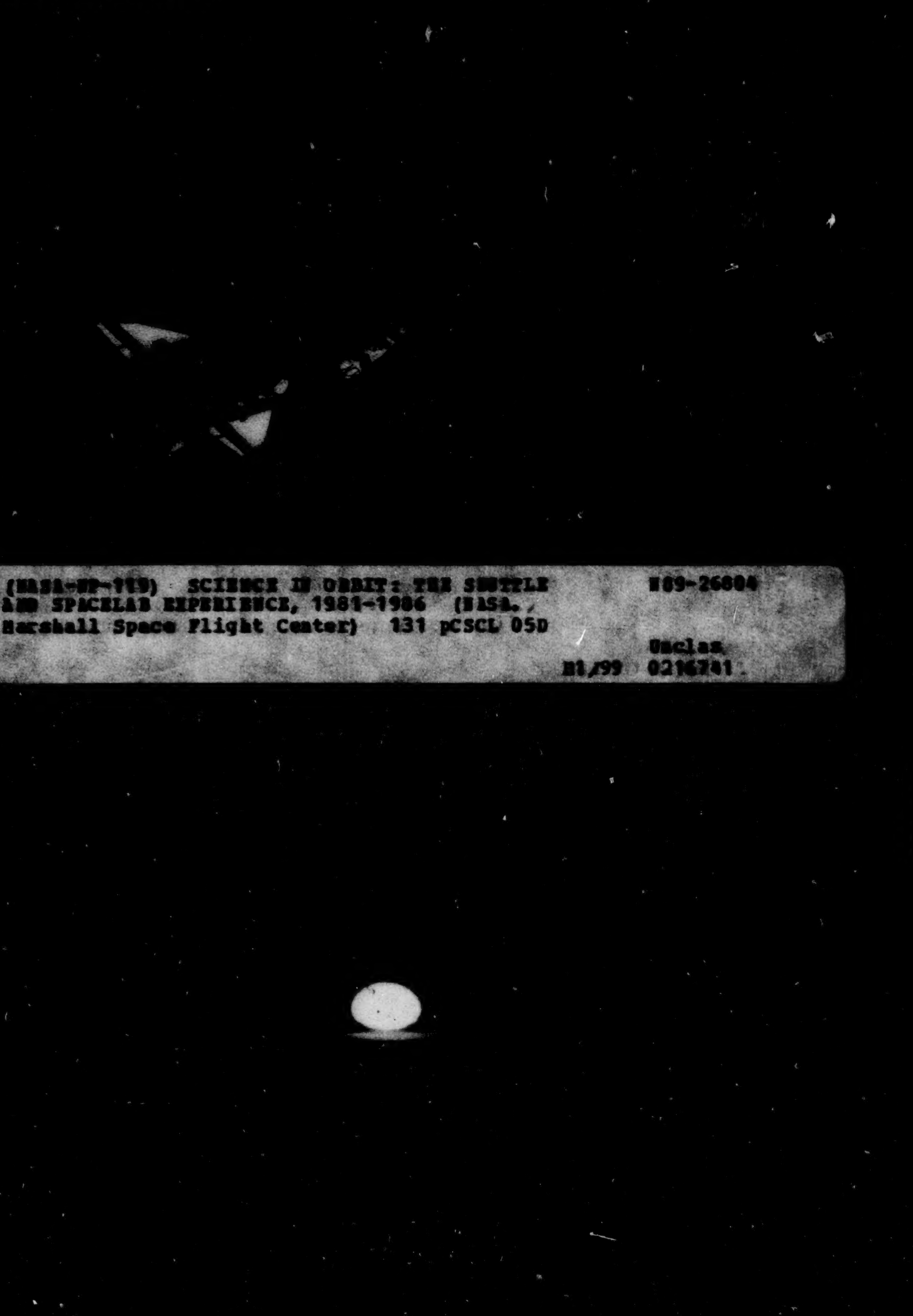

(NASA-NP-119) SCIENCE IN ORBIT: THE SHUTTLE AND SPACELAB EXPERIENCE, 1981-1986 (NASA. Marshall Space Flight Center) 131 p CSCL 05D

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Science in Orbit
The Shuttle & Spacelab Experience: 1981-1986

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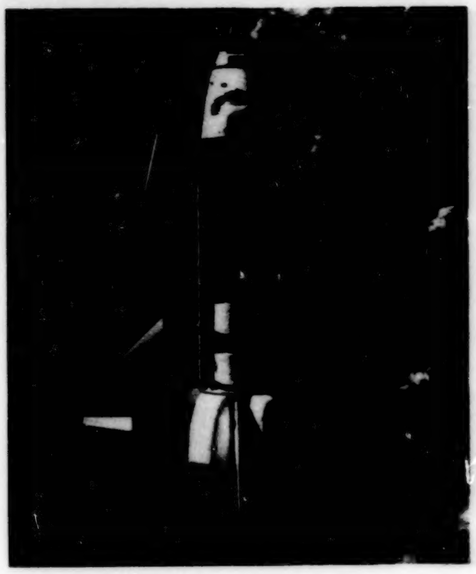

Prepared by
Marshall Space Flight Center
Huntsville, Alabama
1988

NASA
National Aeronautics and
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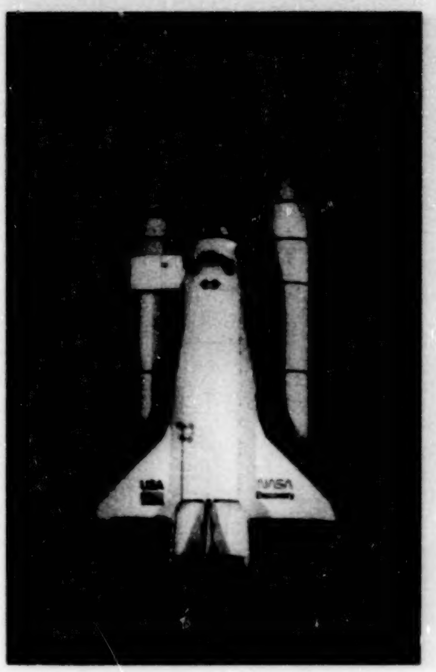
Foreword



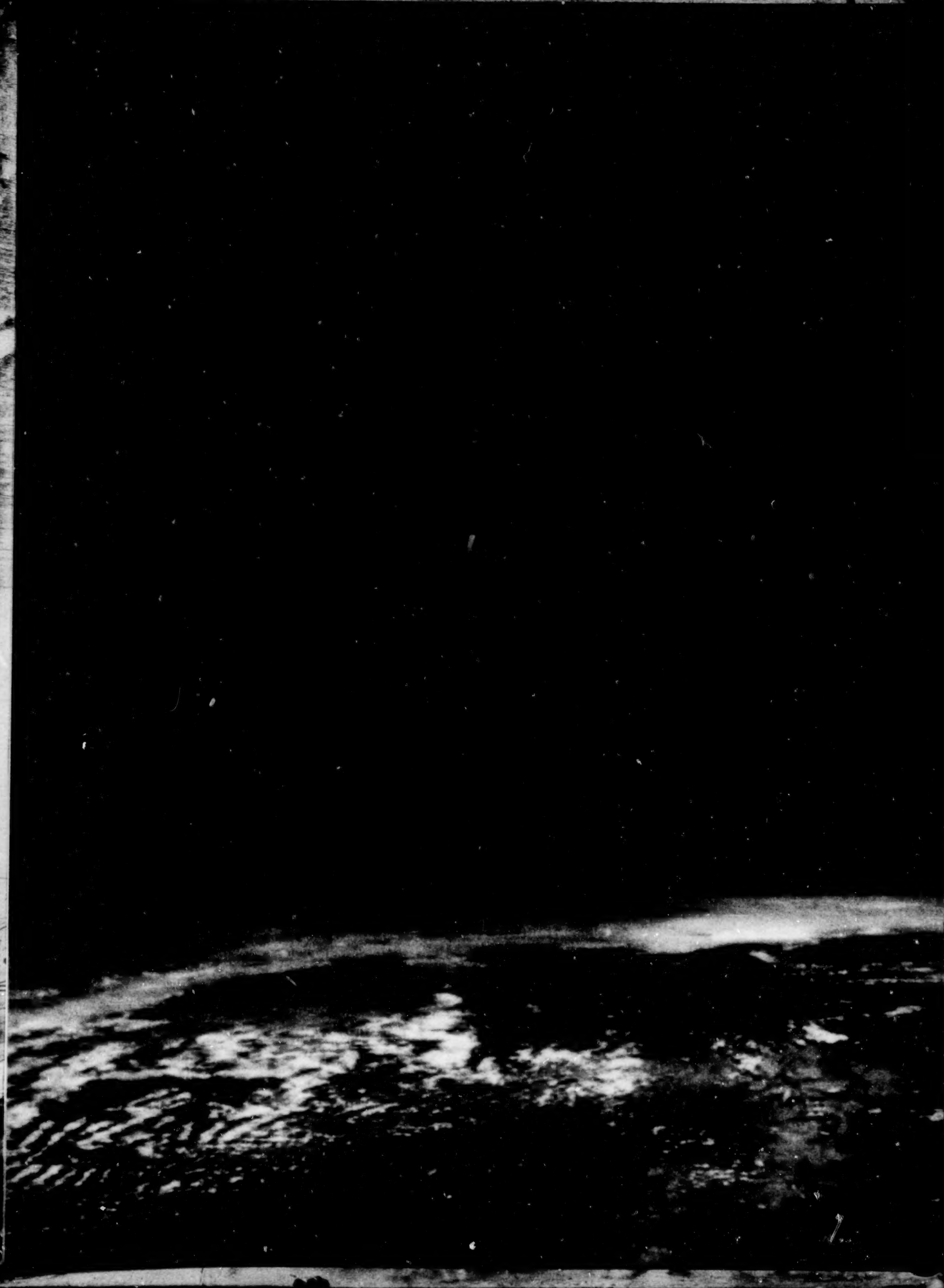
Reviewing the record of the Space Shuttle's first five years in service, one is impressed by the varied program of onboard research in space science and applications. The Shuttle has hosted hundreds of investigations in astronomy, atmospheric science, Earth observations, life sciences, materials science, solar physics, space plasma physics, technology, and other scientific disciplines – investigations developed by scientists around the world. Equipped with the Spacelab elements provided by the European Space Agency, the Shuttle offers both an enclosed laboratory and an exposed platform for investigations in space; crewmembers conduct or monitor the experiments in a manner similar to working in a laboratory on the ground. The Shuttle is a valuable addition to the complement of balloons, aircraft, sounding rockets, and expendable launch vehicles that are already available to space scientists.

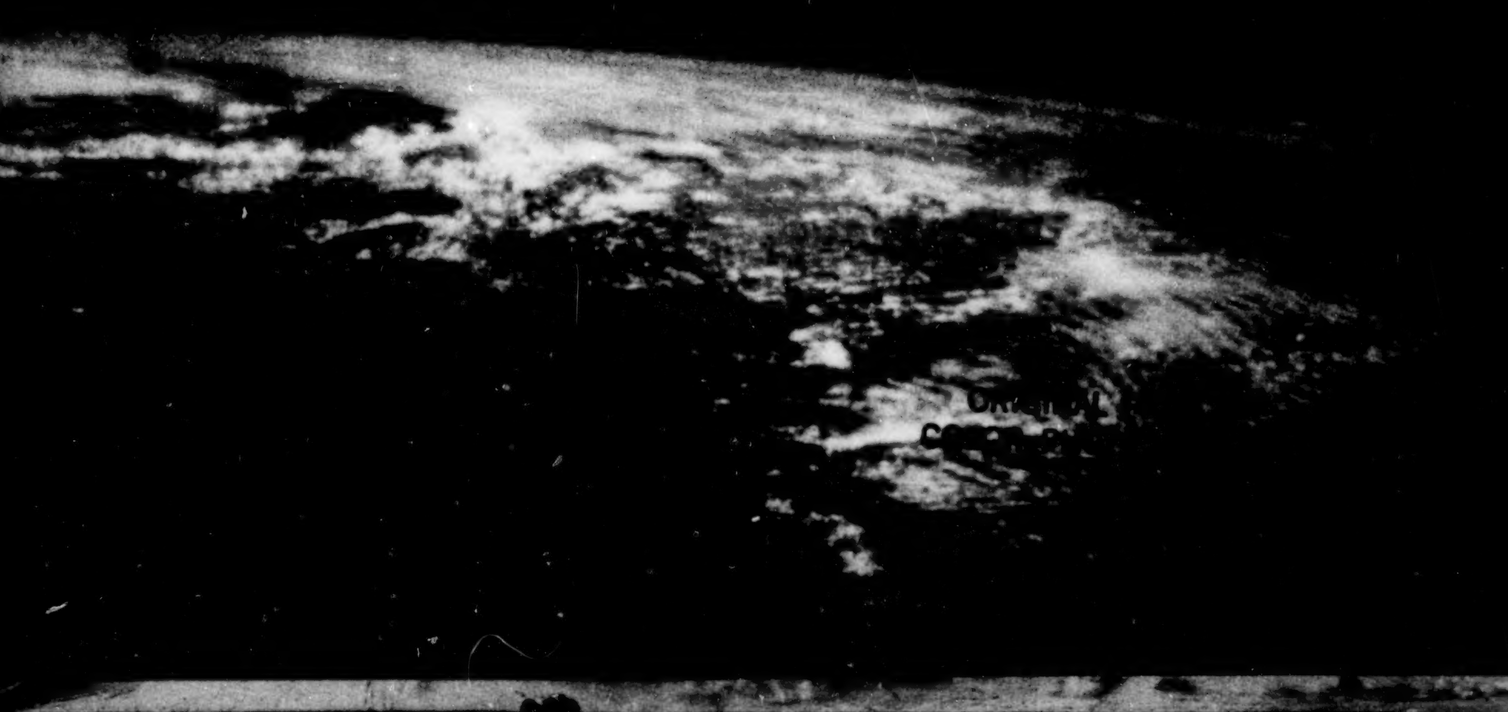
Individual news releases and journal articles have reported results of Shuttle-era research on a case-by-case basis, but this report is a comprehensive overview of significant achievements across all the disciplines and missions in the first generation of Shuttle flights.

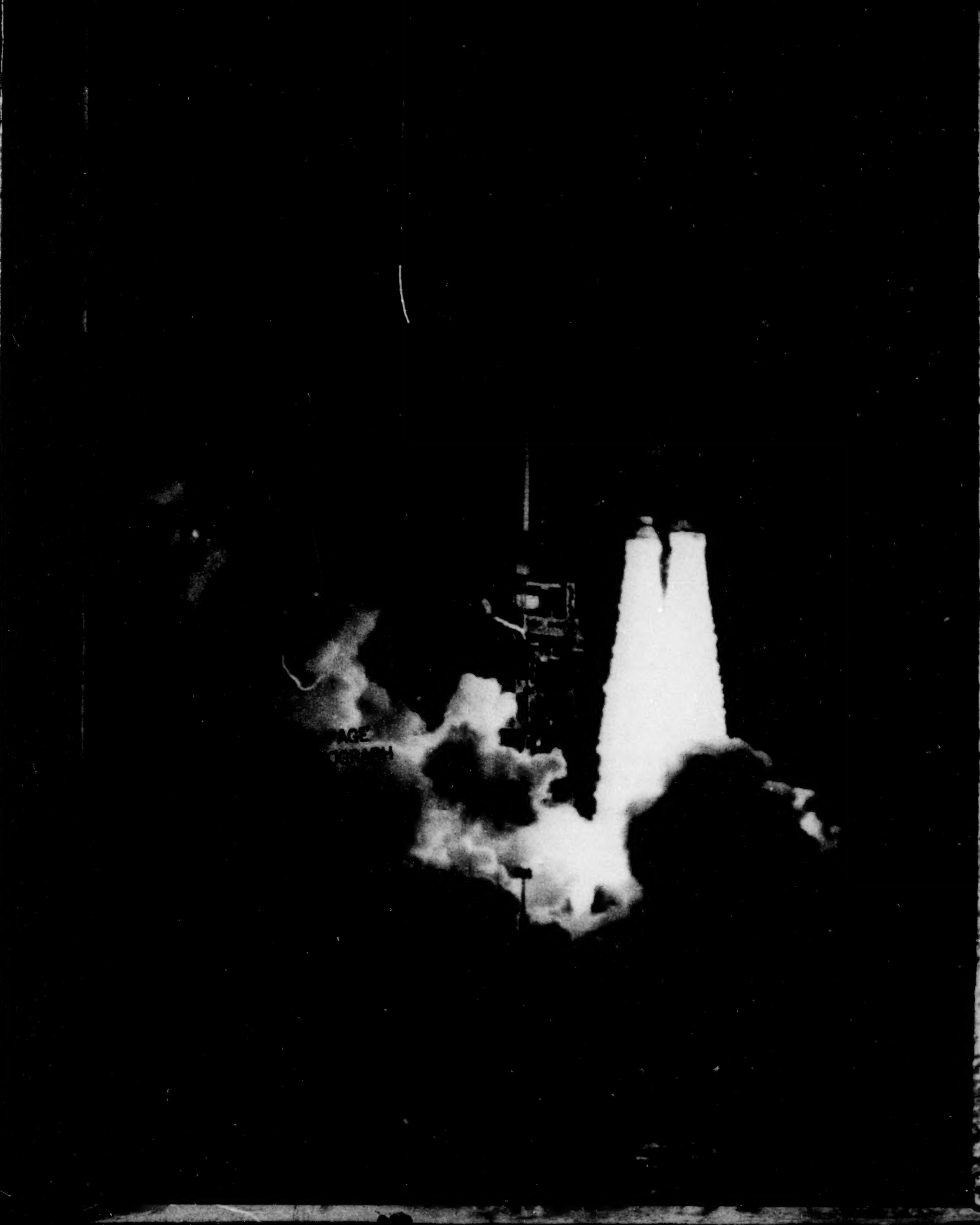
Although the activities reviewed and summarized in this report precede my tenure as Associate Administrator at NASA, it is a pleasure for me to acknowledge here the dedication and enthusiasm of the many individuals in our government and academic institutions, as well as their many support contractors and international associates, who have made these successes possible. As we return the Shuttle to spaceflight, I look forward not only to the renewed vigor of an active science and applications program using the Shuttle but also to the evolution of space science toward a new research capability – Space Station.

L.A. Fisk
Associate Administrator for
Space Science and Applications

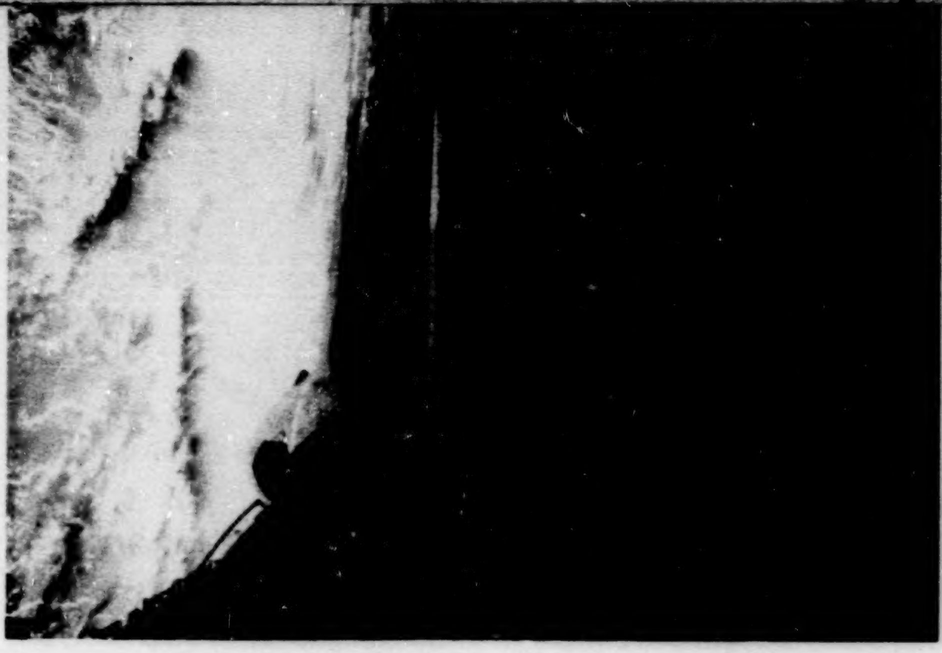
June 1988







Chapter 1

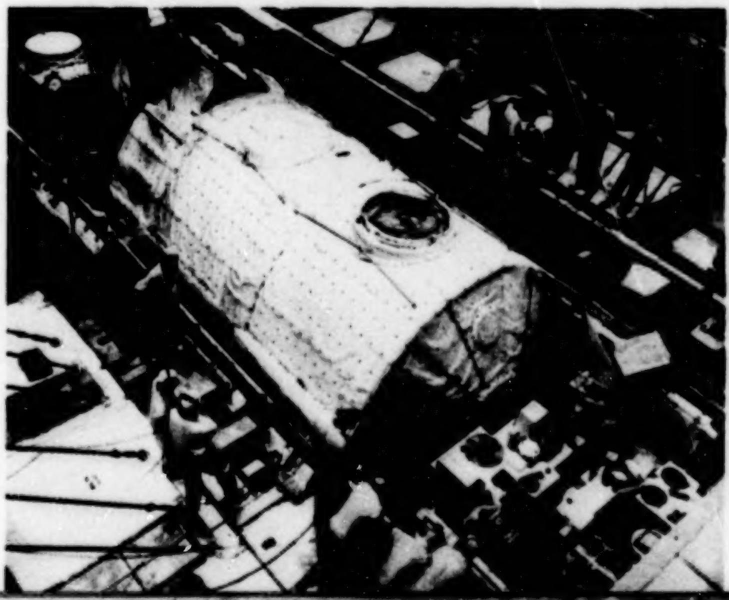


Science on the Space Shuttle and Spacelab

More than a decade ago when the National Aeronautics and Space Administration (NASA) began to design a new launch vehicle, planners envisioned an important use of the Space Shuttle: scientific research.

The outlook was promising. The Shuttle could be used as a platform for observatories to study the Earth and sky; it could serve as host to a laboratory for experiments in the life and materials sciences; it could be a testbed for technology development leading to improved scientific instruments; and the Shuttle itself could be treated as an apparatus for plasma physics experiments in the vast natural laboratory of space. Scientists who were not astronauts would have the rare opportunity to work in space, to escape some of the physical conditions that limit their research on the ground. The pioneering Skylab missions (1973-1974) had proven that surprises would reward those who took the opportunity to do research in space. The prospect of a new merger of science and manned spaceflight was exhilarating.

In a parallel effort during the years of the Shuttle's development, NASA acquired the necessary accommodations for science activities aboard the Shuttle. These include Spacelab, a large, modular laboratory developed by the European Space Agency (ESA), and a set of experiment support structures and carriers, all designed for use in the payload bay. Spacelab is the premier facility for scientific research on the Shuttle; it consists of pressurized laboratory modules and unpressurized pallets that can be used in various combinations for different types of missions. Scientists around the world have developed experiment ideas and hardware for flight in the Shuttle and Spacelab.



Putting Spacelab in the Space Shuttle

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Skylab: America's first orbital laboratory

The Space Shuttle and its companion Spacelab have served science well. During its first 5 years in operation (1981 to 1986), the Shuttle was used repeatedly, with great success, as a research facility for experiments in many of the scientific disciplines. Besides offering enhanced capabilities to the sciences that already had ventured into space, such as solar and plasma physics, the Shuttle opened the way for new research in disciplines with less experience in space, such as biology and materials science. Results from a dozen science missions testify to the value of the Shuttle and Spacelab for manned space science, from experiments that extend current knowledge to bold investigations that attempt what is impossible on Earth.

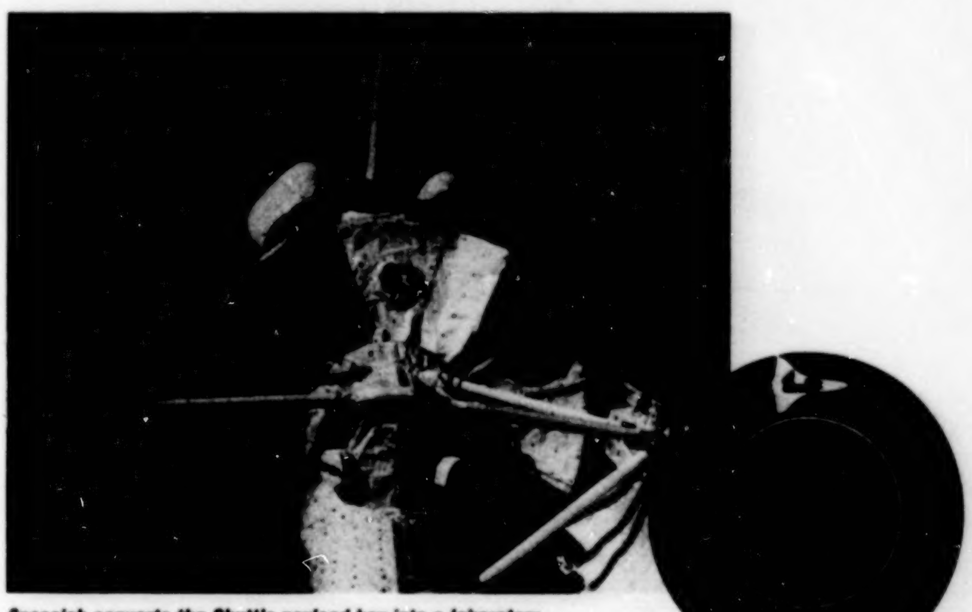
The great variety of experiments flown in Spacelab and other Shuttle attached payloads is impressive. More significant, however, is the tangible gain from space science research. Scientists in fields as different as astronomy, biology, and crystallography are reporting major discoveries from their investigations in space. Furthermore, they are learning how to pursue scientific research in the unfamiliar space environment, refining their experiment techniques and instruments to push the bounds of knowledge ever farther. As data from the "first generation" of science missions in the Shuttle era are being understood, scientists are moving ahead into the next phase of research.

The story of Spacelab and other Shuttle attached payloads is one of opportunity and discovery. This report presents a summary of results to date from many of the scientific investigations conducted aboard the Shuttle. These results are the prelude to the next phase of Shuttle/Spacelab research activity and ultimately to manned space science in the Space Station era.

The Shuttle/Spacelab Opportunity: Before the Space Shuttle and Spacelab came into service, most scientific research in space was conducted via automated instruments on rockets and satellites. There are several limitations in using these unmanned vehicles for science: there is no possibility of direct "hands on" interaction with an experiment, either for operations or for equipment repair, except by remotely controlled computer commands; the rockets offer only a few minutes in space for very small payloads; the satellite-borne instruments can operate for a long time but cannot be recovered for calibration, analysis, or refurbishment. While satellites are useful for long-term observations at distances far from Earth and rockets are useful for short forays into weightlessness, both methods are unsuitable for laboratory science as it is practiced on the ground.

In 1973, the United States launched its first orbital laboratory, Skylab, which was occupied three times for periods of 1 to 3 months. Skylab pioneered the way for manned space science. It was designed for simultaneous research in several disciplines, and its crews included a new breed of scientist-astronauts, selected for their abilities in scientific research. The payload included experiments in solar and stellar astronomy, Earth observations, materials processing, technology, and life sciences.

From the Skylab missions, scientists learned much about doing research in the unfamiliar environment of space. Because the discoveries and data acquired were far greater than anticipated, many new scientific questions were raised. Unfortunately, the program ended after only three manned missions, before many of the new questions could be answered. During the decade-long hiatus in manned space science before the first Spacelab mission, investigators built upon the



Spacelab converts the Shuttle payload bay into a laboratory.

Skylab experience to develop experiments and equipment for flights on the Shuttle.

The Shuttle/Spacelab combination offers an alternative to the limitations of unmanned spacecraft and an exciting variation on the Skylab concept. By permitting scientists to serve as crewmembers (payload and mission specialists) and by providing various experiment accommodations, as in the Skylab era, NASA has merged science with manned spaceflight. Interactive, "hands on" involvement is again possible as the crewmembers perform experiments, monitor and respond to results, and repair equipment when necessary.

With access to space via the Shuttle, scientists hope to accelerate the pace of research. Instruments can be carried into space for 7 to 10 days, returned, modified and refined, and reflown on another mission. Reflight allows investigators to use what they have learned from one mission to plan the next. Furthermore, scientists can now concentrate on what they do best – developing and perfecting investigations – without also having to build a spacecraft to carry them.

Science Missions: Half of the 24 Shuttle flights from 1981 into 1986 carried major scientific payloads, 4 of them Spacelabs, with more than 200 investigations. The early science missions were named after the NASA office that sponsored the payload (such as the Office of Space Science/OSS) and often carried a payload with varied experiments that tested the Shuttle's capabilities for doing space science. While not all Shuttle missions have been dedicated to science, scientific experiments have been done on almost every mission.

Experiments have been successfully conducted in disciplines as diverse as life sciences, materials processing, fluid mechanics, solar-terrestrial physics, astronomy and astrophysics, atmospheric science, Earth observations, and basic technology. Early results from these missions suggest that the spectrum of possibilities for scientific research in space is virtually unlimited.

During most of these missions, experiment progress was monitored instantaneously, in "real time," by audio and video communications with the onboard crew and by data transmitted to the ground. Scientists on the

The Shuttle and Spacelab offer advantages for space science:

Onboard experts who conduct and monitor experiments, maintain equipment, serve as test subjects, evaluate data, and make decisions in much the same way that scientists work in laboratories and observatories on the ground

Enough time in space to do significant microgravity experiments and accumulate data

An experiment site in the ionosphere, allowing the environment to be sampled and probed directly

An observatory base for a global view of Earth and an unobscured view of the universe

The ability to retrieve and return experiment samples and equipment for analysis on the ground and possible reflight

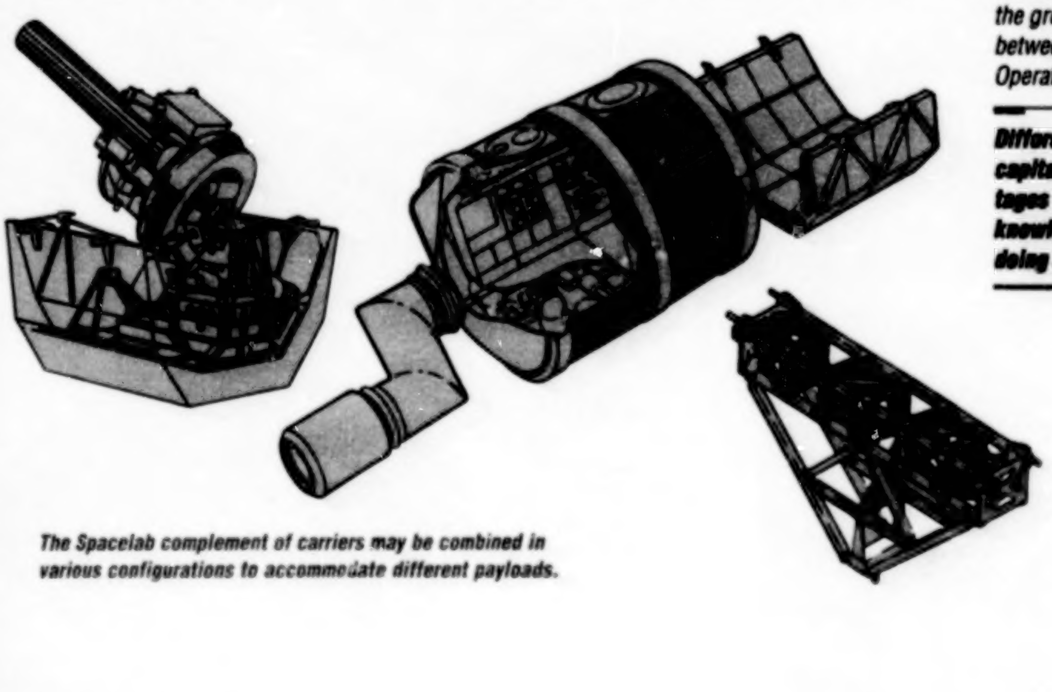
Use of larger, more capable instruments and new techniques in space

Opportunities to perform joint experiments with separate but complementary instruments

A testbed for new equipment and research techniques

Teamwork between scientists in space and on the ground through live voice and data links between the Shuttle and the Payload Operations Control Center.

Different experiments and different fields capitalize on one or more of these advantages to explore the unknown and extend knowledge beyond present limits, to learn by doing and refining.



The Spacelab complement of carriers may be combined in various configurations to accommodate different payloads.

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ground were able to begin immediate analysis of the data from space, and they participated actively in conducting their experiments. It was not uncommon to hear cheers and applause in the Payload Operations Control Center as results came streaming in with hints of discovery.

For a week or more, excitement built as teams of scientists and mission support personnel on the ground worked with the orbiter crew to take advantage of the unique research opportunities in space. The onboard specialists concentrated on getting the maximum yield from every precious minute. By the end of a mission, miles of videotape, dozens of samples, hundreds of photographs, and millions upon millions of bits of data were accumulated for study.

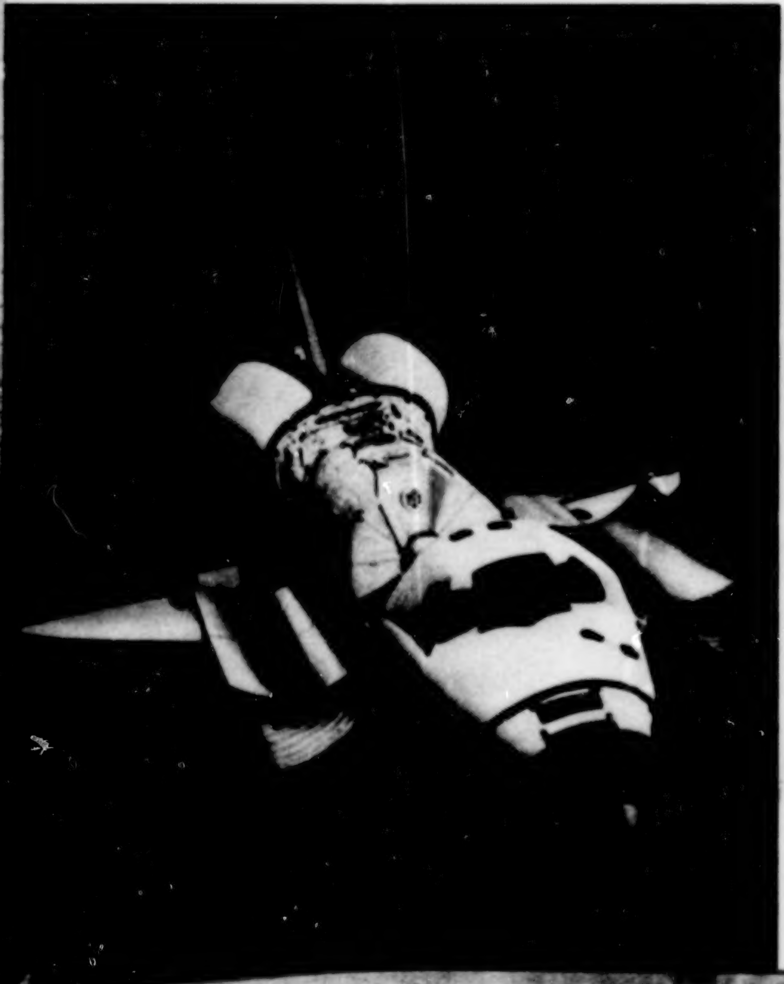
On the Shuttle and Spacelab, scientific research has even greater immediacy and intensity than that experienced in a laboratory on the ground. If an experiment does not proceed as anticipated, scientists can intervene, change procedures, adjust equipment, and respond to the situation at hand. This capability, not available since the Skylab era, gives us a new chance to make discoveries that are beyond our reach on Earth.

Many scientists have invested a large part of their careers in developing experiments for flight. After flight, they reap the rewards of a well-deserved period of analysis to glean new understanding from the mass of data acquired on their mission. With expectancy, painstaking study, occasional disappointment, and eventual revelation, they are using space as the ultimate laboratory and observatory.

This report summarizes some of the significant results from Spacelab and other science missions on the Shuttle during its first 5 years in service. To create a coherent picture, the results are discussed by discipline rather than by mission; thus, an investigation may be seen in the context of similar or related investigations for a clearer sense of the aims and accomplishments in each research field.

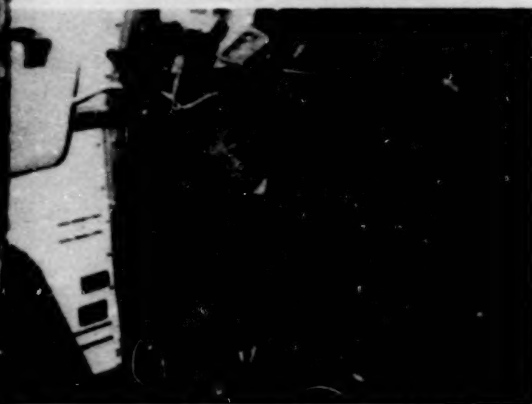
These results herald the advances that are expected when scientists resume experiments on the Space Shuttle and later attain a permanent presence in space on the Space Station. ■

During missions, scientists monitor data and control instruments from the Payload Operations Control Center.



Spacelab 1 was staffed by the first payload specialists, scientists on leave from their laboratories to do research in space. During the 10-day mission, two payload specialists and two mission specialists accomplished more than 70 experiments in 7 disciplines.

The Spacelab 1 mission included experiments inside a laboratory module and on a platform exposed to space. The Spacelab 3 mission also used a module as its main component.

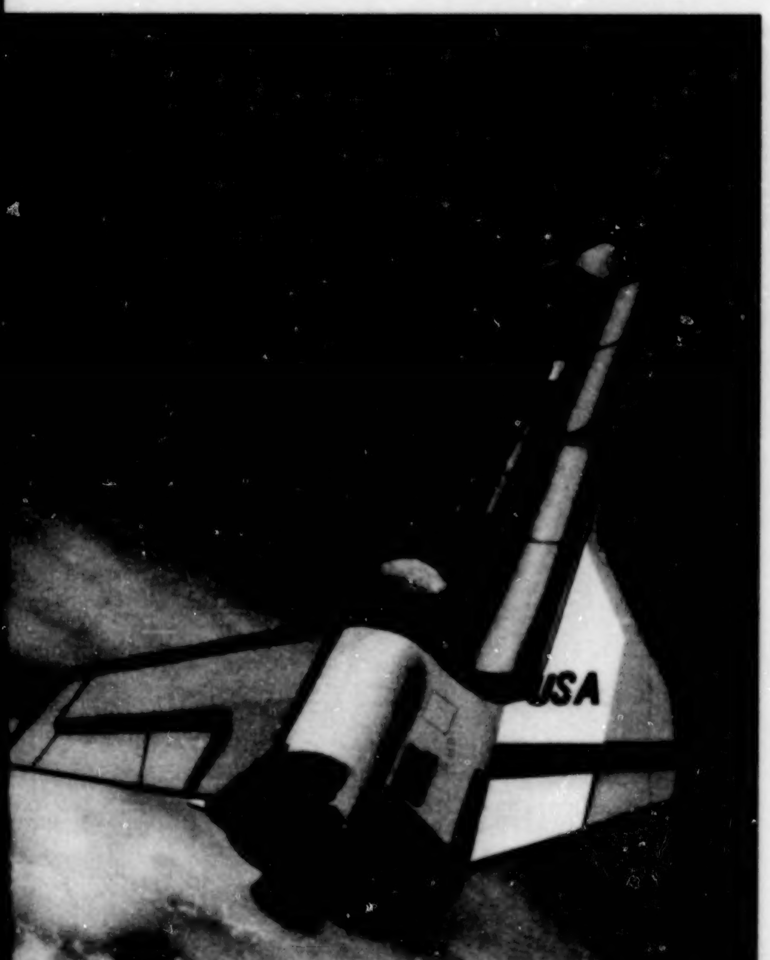


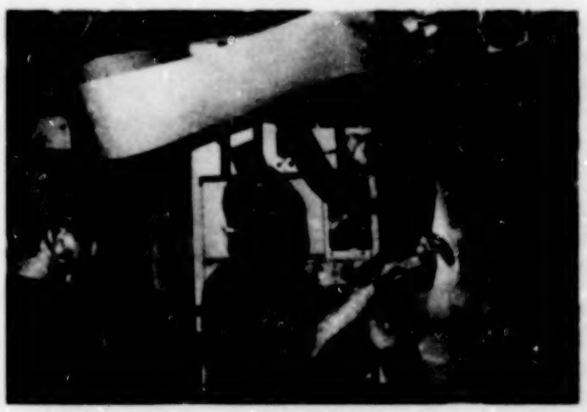
During the Spacelab 3 mission, a payload specialist repaired a research facility in time to complete fluid physics experiments successfully. Meanwhile fellow crewmembers carried out crystal growth and life science experiments.

Spacelab and Other Major Science Payloads on the Shuttle

Payload	Flight	Date
Office of Space & Terrestrial Applications-1 (OSTA-1)	STS-2	Nov. 12–14, 1981
Office of Space Science-1 (OSS-1)	STS-3	Mar. 22–30, 1982
OSTA-2		
Materials Experiment Assembly-A1 (MEA-A1)	STS-7	Jun. 18–24, 1983
MAUS		
Spacelab 1	STS-9	Nov. 28–Dec. 8, 1983
Office of Aeronautics & Space Technology-1 (OAST-1)	41-D	Aug. 30–Sep. 5, 1984
OSTA-3	41-G	Oct. 5–13, 1984
Spacelab 3	51-B	Apr. 29–May 6, 1985
Spartan 1	51-G	Jun. 17–24, 1985
Spacelab 2	51-F	Jul. 29–Aug. 6, 1985
Spacelab D1	61-A	Oct. 30–Nov. 6, 1985
Materials Experiment Assembly-A2 (MEA-A2)		
EASE/ACCESS	61-B	Nov. 26–Dec. 3, 1985
Materials Science Laboratory-2 (MSL-2)	61-C	Jan. 12–18, 1986
Goddard Hitchhiker-1 (HH-G1)		

Middeck experiments, student experiments, Get-Away-Specials, and Detailed Supplementary Objectives are not included in this list, but they have contributed to the body of scientific data and have stimulated ideas and tested equipment and techniques for expanded investigations.





Spacelab 2 was operated like a ground-based observatory, with scientists on the ground monitoring solar activity and sending observing plans to the crew. Crewmembers received teleprinter messages describing the solar viewing agenda for each orbit.

The Spacelab 2 mission used three platforms covered with scientific instruments to form a solar and astronomical observatory.

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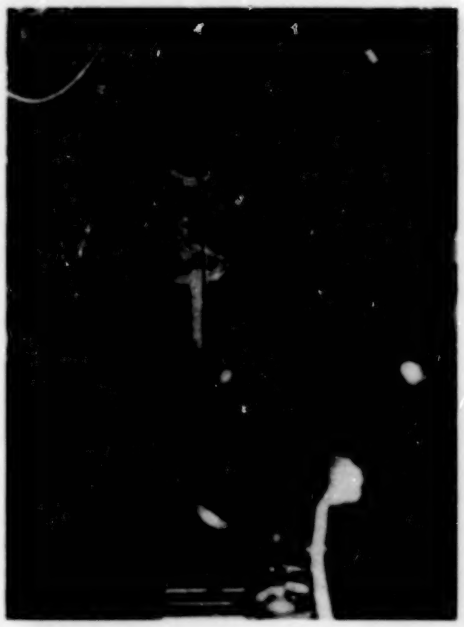
Chapter 2

Living and Working in Space: Life Sciences



To help solve the mysteries of human adaptation to space, crewmembers serve as test subjects. Here, a Spacelab 1 payload specialist exercises while instruments measure his heart's operation in microgravity.

Research in space has given us tantalizing glimpses into the nature of life and the influence of gravity on living things. In space, scientists have been able to examine how life adapts to a different environment and thereby gain new knowledge about basic life processes on Earth.

Early life sciences experiments in orbit raised many questions about how the interrelated systems of the human body and other living organisms react to microgravity. How does the human body adjust as microgravity causes fluid to shift toward the head? Do muscles and bones degrade without the force of gravity to work against? What causes some people to experience symptoms similar to motion sickness during the first few days in space while others have no symptoms? How do plants behave when there is no up or down? Do cells reproduce and synthesize materials normally in space? What are the consequences of these reactions? If responses to the space environment are undesirable, how can we prevent or control them?

The Shuttle/Spacelab facilities have given scientists increased opportunities to explore these and many other questions. Investigators are studying diverse life forms from cells to whole organisms, including the human body with its many complex systems. The Spacelab module offers enough room for various experiment apparatus and an environment with regulated temperatures and pressure. To maximize scientific return, the space laboratory equipment includes modified standard medical tools, multipurpose reusable minilabs, and plant and animal habitats.

Most importantly, the Spacelab module accommodates a staff of trained scientists. Life science research in space demands heavy crew involvement as expert investigators, test subjects, and laboratory technicians. Crewmembers draw and process blood samples, record their own physiological symptoms, set up and participate in a variety of experiments, tend plant and animal experiments, and carry on their work much as they do in laboratories on the ground. Detailed research in this field was very limited until the Shuttle and Spacelab made a manned laboratory in space possible.

Many of the experiments performed to date have synergistic results. Physiology experiments on various parts of the body, such as the heart, muscles, and bones, are all related because changes in one part of the body cause a ripple effect inducing changes elsewhere. The human and animal studies often parallel each other as scientists attempt to determine whether the changes occurring in animals are similar to those observed in humans. If animals can be used as models for people, the number and type of studies can be increased because more subjects will be available.

Other experiments explore fundamental questions in biology by studying life – from single cells to complex organisms – in the microgravity

Crewmembers donate their blood for life sciences research.

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environment. This knowledge can be transferred to the medical and biological communities to improve the quality of life on Earth. If cells can reproduce and synthesize materials normally or better in weightlessness, some of their products that are of commercial and pharmaceutical importance may be produced in purer forms in orbit. Many important biological molecules have never been structurally analyzed before, but in microgravity it may be possible to produce protein crystals, for example, that are large and pure enough for more precise analysis.

This vigorous inquiry into the nature of life meets NASA's major goals: to ensure the safety and comfort of people living and working in space, enabling even longer stays in space, and to explore the fundamental nature of life in the universe. Shuttle experiments have begun to confirm some generally held hypotheses and also have surprised investigators with unexpected results. At this point, we have gleaned only nuggets of information, pieces of a puzzle that must be worked out during future comprehensive investigations. The harvest of life sciences data from the Shuttle and Spacelab missions contains the seeds for more complex, long-term experiments aboard the Space Station.

Spacelab results indicate that squirrel monkeys adapt to microgravity in a similar fashion to humans.

Plants may grow differently in space. Roots protruded above the soil when mung beans were grown in the Shuttle.

Physiology: After more than 25 years of spaceflight, life scientists remain eager to study the body and its healthy but somewhat changed functioning in space. Through centuries of evolution, the human body has adapted to gravity's demands in countless subtle ways. In the absence of gravity, the body undergoes noticeable physiological changes: blood and body fluids are redistributed, affecting the circulatory and endocrine systems; muscles and bones begin to deteriorate; and some sensory signals are scrambled.

Scientists are seeking to understand the various bodily responses to spaceflight. Many Shuttle/Spacelab experiments attempt to test or confirm theoretical explanations of how the body reacts in space and why. In microgravity, the body is in a state of "free fall" and reacts as if there is no gravity. According to one current hypothesis, the absence of gravity results in a redistribution of fluids to the upper body; this adversely affects the homeostatic mechanisms that control the cardiovascular, endocrine, and metabolic systems. A reduction of forces on the body may explain the muscle and bone degradation that has been observed in space crews and animal test subjects.

Another physiological response to spaceflight that remains a mystery is the discomfort similar to motion sickness that about half of space crews experience during their first few days in

It may be possible to grow nearly perfect protein crystals in space for studies of protein structures, such as the one shown in this computer model.

space. Scientists theorize that normal sensory and motor cues from the vestibular system in the inner ear, the eyes, and the nervous system are altered in microgravity and may conflict. For example, the eyes may send one message about body orientation while the inner ear sends another. As the person adapts to microgravity, the brain learns to reinterpret or ignore confusing signals.

None of the findings to date proves that the body's responses are pathological. Some appear to be appropriate and effective ways to adapt to a new environment. Others such as the immune response and muscle and bone degradation must be studied in greater detail during longer missions. Scientists must not only identify detrimental responses but also find ways to prevent such responses so that crews can be qualified for long-term space missions aboard the Space Station and throughout the solar system.

Cardiovascular System: On Earth, the parts of the cardiovascular system (the heart, lungs, and blood vessels) work together in a stable state of equilibrium. In weightlessness, blood and other fluids are redistributed to the head and upper body. In response to the fluid shift, the body's normal homeostatic mechanisms appear to adjust the operation of the heart and other parts of the body.

For Spacelab research, an instrument was developed to record changes as the heart adjusts to microgravity. Called an echocardiograph, the instrument generates two-dimensional images by interpreting high-frequency sound waves directed at the heart. It was tested during Shuttle mission 51-D in April 1985 when real-time images of four crewmembers' hearts revealed major cardiovascular adjustments during the first day of spaceflight. The left side of the heart (which propels blood through the circulatory system) reached its maximum size, as did the blood volume it pumps, on the first day; the right side of the heart (which collects blood returning from the rest of the body) was smaller than when imaged preflight. By the second day of the mission, the entire heart was smaller and subsequent changes progressed more slowly. The reduction in the left heart volume remained unchanged for at least 1 week after return to Earth.

From these observations, investigators concluded that the cardiovascular system adjusts quickly to fluid shifts and blood volume loss during spaceflight. Results from a French echocardiograph flown on the 51-G mission confirmed the U.S. observations on the 51-D mission. More extensive tests are needed to determine if the decrease in heart volume is associated with any reductions in heart performance. A U.S. echocardiograph is scheduled to be flown again with complementary instruments on a mission dedicated to life sciences research.

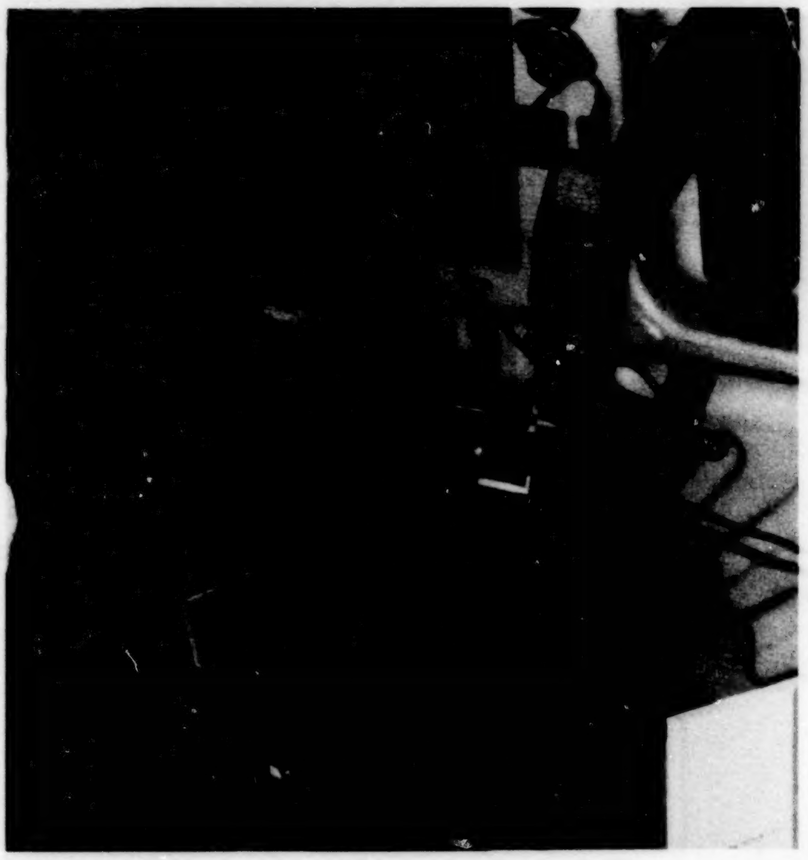
Since changes in the heart appear to be linked directly to fluid shifts, it is important to track the time course of fluid shifts in microgravity. One way to measure changes in the amount of fluid in the upper body is to measure corresponding changes in the circulatory system. As fluid volume increases, scientists have predicted that more pressure than usual should be exerted on the upper body veins; as upward fluid flow decreases, the pressure should equalize. Spacelab 1 investigators tried to determine the degree and rapidity of the fluid shift by measuring central venous pressure in the arm veins of four crewmembers. Before this mission, no direct measurements of venous pressure were available to test the hypothesis.

Surprisingly when venous pressure was measured 22 hours into the mission, it was lower, not higher, than preflight measurements. One hour after landing, venous pressures were high for all four crewmembers, indicating fluid shifts associated with the body's readaptation to Earth.

Astronauts use the echocardiograph to record images of the heart as the body adapts to microgravity.

This experiment was repeated using four different subjects on the Spacelab D1 mission with measurements made as early as 20 minutes after launch. Even with early measurements, the venous pressure was still lower than the preflight measurements, confirming the Spacelab 1 results. The investigator was astonished at the low pressure level so early in the mission before any dehydration was possible.

From these results, investigators concluded that the fluid shift is a highly dynamic process that may occur even before launch when crewmembers spend about 2 hours seated in the Shuttle on the launch pad. To confirm this hypothesis, investigators want to make measurements during this waiting period along with measurements of hormones that regulate fluid balance. A novel device for noninvasively measuring venous pressure may help clarify the profile of fluid shifts by enabling more frequent and convenient measurements. Limited measurements with the device, which was tested on the 61-C mission, confirm the Spacelab 1 and Spacelab D1 results.



The shift of body fluid toward the head during spaceflight may initiate cardiovascular adaptation to space. Determining venous pressure by measuring blood flow in the jugular vein may help to define the timetable for fluid shifts and space adaptation.

Hematology and Immunology: Red blood cells, which are the focus of the hematology studies, transport oxygen throughout the body. Spaceflight studies indicate that red blood cell mass is reduced in microgravity. Several theories as to why this happens have been developed. One of the most generally accepted is that bone marrow function is inhibited; this results in the suppression of erythropoietin, a hormone that stimulates red blood cell creation.

A Spacelab 1 investigation studied the relationship between decreases in erythropoietin and red blood cell mass by analyzing blood samples from four crewmembers taken before, during, and after flight. While there was a significant decrease in red blood cell mass and reticulocytes, erythropoietin seemed not to vary significantly. More studies are needed to determine if the body destroys red blood cells or if other mechanisms influence red blood cell counts.

Another important type of cell, lymphocytes (white blood cells), may also be altered in microgravity. Lymphocytes help the body resist infection by recognizing harmful foreign agents and eliminating them. Some evidence from previous space studies suggests that the number and effectiveness of white blood cells are reduced in space crews, and thus the ability to fight infection is altered. However, astronauts have not shown an increased susceptibility to disease, and lymphocyte counts return to normal a few weeks after landing.

An experiment flown on Spacelab 1 and repeated on Spacelab D1 contributed substantially to the understanding of the immune system's operation in space. Before white blood cells can recognize a harmful substance and multiply to eliminate it, the cells go through a process called activation in which they identify the foreign substance, differentiate to enable the production of the appropriate antibody,

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Biologists are studying the effects of microgravity on red blood cell development. The arrow in this electron microscope image (magnification 1,600 times) shows a reticulocyte, a young developing red blood cell, surrounded by mature red blood cells.

These electron microscope images (magnification 6,000 times) show several shapes assumed by red blood cells. Spaceflight appears to result in an increase in unusual shapes. The upper left quadrant shows a normal red blood cell shape, and the lower left shows an echinocyte, a rare shape. Normally, very few echinocytes are found in the blood, but in samples obtained from Spacelab 1 crewmembers a week after landing, more of these cells were found than usual. An intermediate stage in the transformation is shown at the upper right and an even rarer cell than the echinocyte is shown at the lower right.

and finally proliferate to produce sufficient amounts of the antibody.

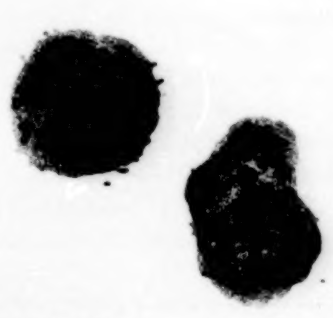
Immune cells cultured during Spacelab 1 lost almost all ability to respond to foreign challenge. Cultures grown in space and controls grown on the ground were injected with mitogen, an agent that causes lymphocytes to activate and reproduce rapidly to fight infection. Proliferation of the flight lymphocytes was less than three percent of that for ground lymphocytes. Although the flight cells were clearly alive, they did not activate and respond to the stimulus.

This experiment was repeated on the D1 mission with cultures exposed to microgravity, cultures on a 1-g centrifuge, and with blood taken from the crewmembers during the mission. Cultures grown on the 1-g centrifuge, which simulates terrestrial gravity, were important controls because other factors besides microgravity (such as radiation) were still candidates for altering the cells' response. The samples taken from the crew were important because only cultures of lymphocytes had been studied during Spacelab 1.

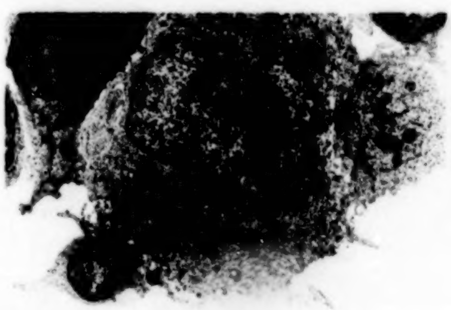
The Spacelab D1 results confirmed the Spacelab 1 results: cell activation in the cultures exposed to microgravity was depressed when compared to control cultures on the centrifuge and on the ground. Since cells on the 1-g centrifuge responded normally, it appears that microgravity is the dominant factor inhibiting cell activation in space. In addition, activation of lymphocytes from the crewmembers was markedly depressed in samples taken in flight as well as in samples drawn an hour after landing; the activation process in crewmembers' white blood cells did not fully return to normal until 1 to 2 weeks after landing.

These two experiments made it clear that microgravity almost completely inhibits the process of lymphocyte activation. In conjunction with other Spacelab D1 results indicating increased proliferation and antibiotic resistance of bacteria in microgravity, these results suggest a risk of infectious disease, which must be taken seriously in planning spaceflights. The next step is to discover which stage of the activation process is affected and determine if the effect can be prevented.

A complementary Spacelab 1 experiment indicates that immunoglobulins (key antibodies) appear to function normally in space. In blood samples from four crewmembers, only minor fluctuations in quantity were measured with no significant effects recorded during the 10-day flight. From these results, one might conclude that activated lymphocytes continue to produce antibodies during prolonged weightlessness and are not affected by microgravity. However, microgravity may impair the lymphocyte activation process, altering the immune system's ability to respond to challenges.



Microgravity cultures



1-g centrifuge cultures

White blood cells cultured in microgravity did not reproduce at normal rates, but white blood cells cultured in space on the 1-g centrifuge proliferated normally. Otherwise, the cells in both cultures are normal. (Electron microscope images, magnification 35,000 times.)

Musculoskeletal System: The muscles and bones, the support structure of the body, evolved under the influence of gravity and now require gravity for normal functioning. In the absence of gravity, muscles may deteriorate and bones may become smaller and weaker. Previous space crews have shown loss of lower body mass, especially in the calves, decreases in muscle strength, and negative calcium balances. The process occurring in space resembles the initial phases of some bone diseases or the wasting away of muscle and bone observed in bedrest patients. Thus, a better understanding of this process in space also will aid research on Earth.

During the Spacelab 2 mission, investigators measured vitamin D metabolites, which regulate calcium in the bones and blood stream. Three vitamin D metabolites were measured in blood samples taken from four crewmembers before, during, and after flight. Levels of two metabolites remained essentially unchanged. However, the level of a third metabolite underwent an interesting pattern: there was a rise in the level in blood samples collected early in the mission, which dropped in samples taken on mission day six and returned to normal postflight. Measured values remained within a normal range at all times, but the pattern exhibited in all four crewmembers needs further examination.

During the Spacelab 3 mission, 24 rodents and 2 squirrel monkeys also occupied the spacecraft. They resided in an animal habitat designed especially for space and were returned to Earth unstressed and in good health, but some physiological changes attributed to weightlessness were observed. Spacelab 3 studies of the rodent musculoskeletal system confirmed some of the changes, such as reduced muscle mass in the legs, that also have been reported by astronauts. Some of the most notable phenomena measured in the rodents were a dramatic loss of muscle mass, increased bone fragility, and bone deterioration. As with humans, the long gravity-sensitive muscles in the rodents' legs and spines seemed to be most affected; some leg and neck muscles lost up to 50 percent of their mass.

Muscle mass in the legs appears to decrease in microgravity. This sock is used to measure changes in leg volume associated with fluid shifts from the lower to upper body.

A hormone change measured in the rodents may be associated with the observed loss of muscle and retarded bone development. Although the pituitary glands of these animals showed an increase in growth hormone content, the release of the hormone appeared to be impaired. This resulted in substantially lower growth hormone synthesis for flight rats than for ground controls. Such indications of a response to microgravity at a cellular level are intriguing and require further investigations.

All of the Spacelab 3 rodents adapted readily to microgravity and were returned to Earth in good health, but they experienced losses of muscle and bone mass and altered hormone production.

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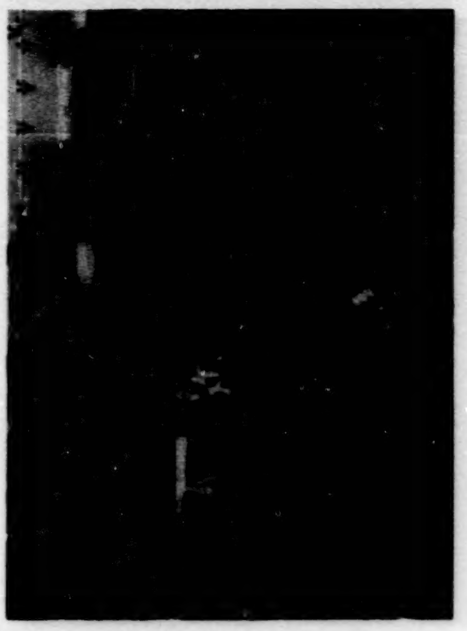
Neurovestibular System: The neurovestibular system, which includes our reflex, vision, and balance organs, appears to be very sensitive to gravity. Space motion sickness, which has affected about half of all space travelers, may be a result of this sensitivity. Symptoms of space sickness include lack of appetite, nausea, and vomiting. Symptoms are similar to motion sickness, but scientists are unsure if the stimulus is the same because crewmembers who are susceptible to motion sickness on Earth may not experience space sickness and vice versa. There is still no good model for predicting whether individuals will experience discomfort as they adapt to space.

Luckily the body adapts quickly, and the most severe symptoms occur during the first days of spaceflight. Although some medications have been used successfully to reduce the symptoms, no treatment eliminates these discomforts. Experiments have focused on identifying the underlying causes of the problem and ways to treat it.

During the Spacelab 1 mission, a group of complementary experiments sponsored by American, Canadian, and European scientists studied the vestibular system from a variety of angles to determine how the sensory motor system adapts to weightlessness. This research focused on the inner ear organs (especially the otoliths) which sense gravity and linear acceleration. The experiments also examined the interrelated functioning of the inner ear, vision, and reflexes – all of which help us orient ourselves.

Before the mission, investigators proposed a "sensory conflict" theory: in microgravity, information sent to the brain from the inner ear and other senses conflicts with the cues expected from past experience in Earth's 1-g environment, resulting in disorientation associated with space adaptation syndrome.



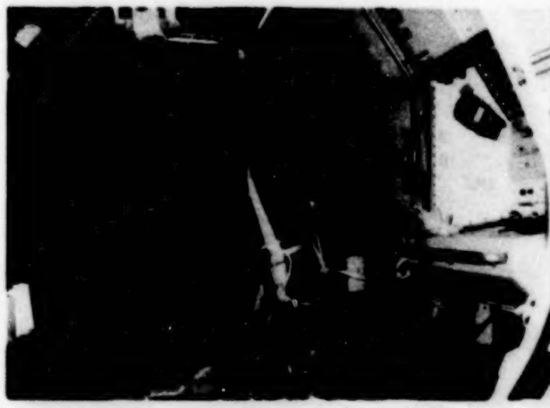
A physiological tape recorder worn by Spacelab 1 crewmembers recorded continuous measurements of brain and heart activity and eye and head movements. Results indicate that head movements and visual disorientation provoke space motion sickness.

During the Spacelab 1 mission, three of four subjects developed space motion sickness. The astronauts made detailed reports on the time course of symptoms while their head movements were monitored with accelerometers. These reports were the first detailed clinical case histories of space sickness available for study. As expected, head movements were reported to provoke episodes of space sickness, but the Spacelab 1 crew also documented the important role played by vision in the adaptation process. Crewmembers frequently experienced a spontaneous change in perceived self-orientation if they reinterpreted the location of various static landmarks or if another crewmember came within view in an unfamiliar orientation. As with head movements, these visual reorientation episodes provoked space sickness. These findings fit the sensory conflict theory, which predicts confusion over actual versus expected sensory cues.

Other experiments examined different outputs to reveal how the central nervous system adapts to microgravity. A rotating dome, a drum with dot patterns that fits around the face and produces a sensation of bodily motion, was used to stimulate eye movements and body reactions. Subjects reported stronger visual effects in space than on the ground, which suggests a greater reliance on vision while signals from the otoliths are ignored or reinterpreted.

On the 41-G and Spacelab 1 missions, subjects experienced some visual illusions as they performed prescribed movement tests. Other tests measured the subjects' changes in perception when blindfolded in weightlessness. When crewmembers viewed various targets and then pointed at them while blindfolded, their perception of target location was very inaccurate in flight compared to similar tests on the ground. In a test of the ability to perceive mass in microgravity, subjects were much more inaccurate in predicting masses in weightlessness than in predicting weights and masses in preflight tests.

The hop and drop experiments studied the otolith-spinal reflex which normally prepares one for landing from a fall. Surface electrodes over the calf muscles recorded neuromuscular signals during simulated falls (accomplished in weightlessness by attaching



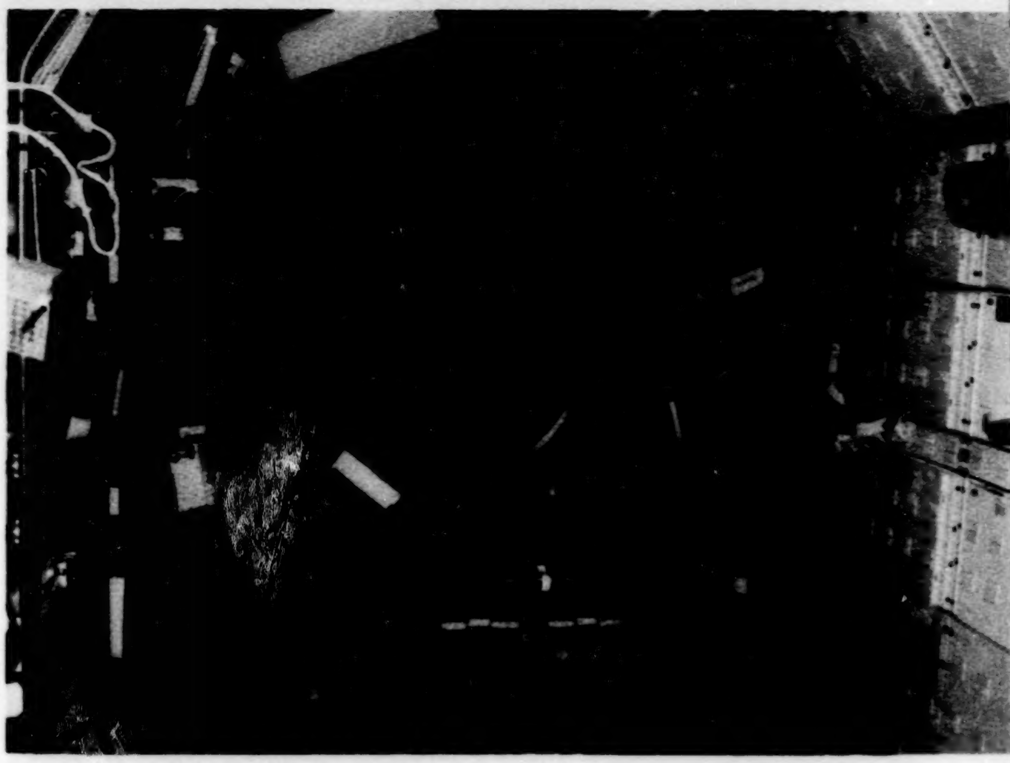
The hop and drop experiment studied the otolith-spinal reflex which normally prepares one to land after a fall. Results indicate that the otolith-spinal reflex response was inhibited in microgravity.

elastic cords to the crewman to pull him downward). The normal reflex was inhibited when tested early in flight, declined further as the flight progressed, but returned to normal during tests conducted immediately after landing. Again, this suggests that in microgravity the brain ignores or reinterprets otolith signals.

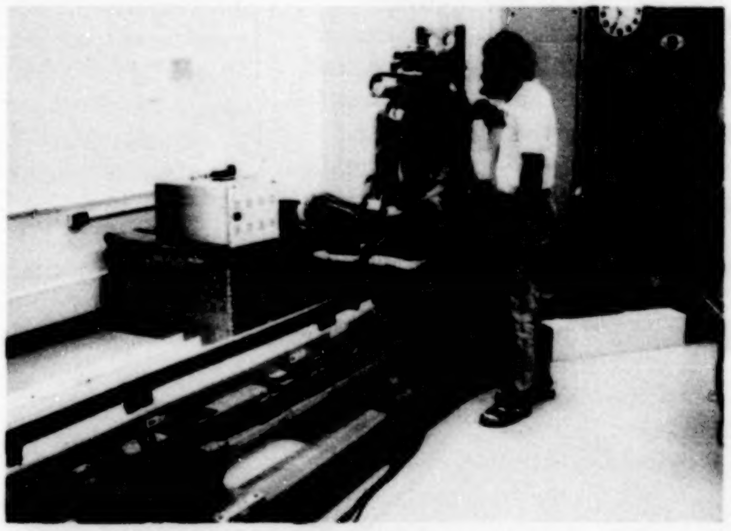
Spacelab 1 experiments studying the vestibulo-spinal reflex mechanisms measured changes in the spinal reflexes and posture associated with the vestibular system. The subjects' physiological responses to standard posture and reflex tests were recorded. Results of these tests indicate that posture is modified dramatically in weightlessness, and the individuals whose central nervous systems are better able to modify response patterns may experience less severe symptoms of space motion sickness. A related French experiment on the 51-G mission revealed changes in muscle movement and the role of vision during postural control.

Pre- and postflight Spacelab 1 tests using a sled to accelerate subjects along a linear path indicated that subjects had an increased ability to perceive linear motion after exposure to microgravity; this seems to indicate that signals sent from the otoliths, which sense both gravity and linear acceleration, come to be interpreted by the brain as only linear motion.

To increase the number of subjects for statistical studies, some of the Spacelab 1 experiments were modified and reflown aboard the Spacelab D1 mission. These included the space motion sickness studies, the rotating dome experiment, and the hop and drop experiment. Although the Spacelab D1 results are still being analyzed, they generally confirm the Spacelab 1 findings.



Spacelab D1 repeated some of the Spacelab 1 vestibular experiments to increase statistical samples and used a linear acceleration sled (center aisle of module) in orbit for the first time.



Tests with acceleration sleds are used to study our perception of and sensitivity to linear motion.

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Spacelab 3 crewmembers wore undergarments outfitted with physiological monitors and kept logs of space motion sickness symptoms.

A sled developed by the European Space Agency was flown in space for the first time on the D1 mission. When subjects were accelerated on the sled in flight, without the influence of gravity, they had smaller increases in sensitivity to linear motion than the investigators expected. Postflight D1 sled experiments confirmed the earlier Spacelab 1 postflight sled tests, with subjects continuing to show slight increases in sensitivity to linear accelerations.

Spacelab 3 results indicated that other mammals may also experience space motion sickness. The two monkeys flown on the mission were carefully observed by trained biologists. The monkeys' patterns of food intake and behavior indicated that while one animal reacted normally throughout the mission, the other had low food consumption for the first four days of flight followed by recovery during the last three days of the mission. Both monkeys' behavior and food consumption were normal upon landing. This suggests that squirrel monkeys may serve as good surrogates for studying space motion sickness.

Another Spacelab 3 experiment tested the effectiveness of the combined use of autogenic and biofeedback training as a countermeasure to space motion sickness. Preflight, two crewmembers were trained to gain voluntary control of their heart rate, skin temperature, and finger pulse rates. Two other crewmembers who served as controls did not receive training. During the flight, each of the four crewmembers wore an undergarment equipped with electrodes and sensors for measuring heart rate, body temperature, skin response, and breathing rate. For the first time during a Shuttle flight, these physiological parameters were recorded continuously during the astronauts' working hours.

Although the statistical sample is small, postflight analysis of crew logs and physiological data indicate that one crewmember who learned to control the motion sickness symptoms with autogenic feedback training preflight was able to use these skills to control minor symptoms experienced in flight. This crewmember never developed any severe symptoms during the mission. The other crewmember who demonstrated less skill with the autogenic feedback training technique reported one severe episode of space motion sickness. The two control subjects (who took anti-motion sickness medication) reported multiple symptom episodes during the first day of the mission. Symptoms for all four subjects subsided after the first day in space. More subjects need to be tested, but initial results seem to indicate that preflight improvements in motion sickness tolerance can be used to predict success in controlling symptoms in flight.

Microgravity also enabled investigators to make a discovery about the inner ear. Since the last century, it has been known that irrigation of the ear canals with water at a temperature higher or lower than body temperature causes nystagmus – rapid involuntary eye movements. This test is important for the clinical diagnosis of sensory problems. According to previous theory, these eye movements are caused primarily by thermal convection in fluid in the semicircular canals of the inner ear. In space, it is possible to test this hypothesis since thermal convection is inhibited by the virtual absence of gravity. When the test was done with two subjects during Spacelab 1, both responded with eye movements. Thus, the presence of caloric nystagmus in microgravity demonstrates that mechanisms other than thermal convection are involved.

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Fundamental Biology: By studying life in a microgravity environment, scientists can see functions that are masked by gravity on Earth. Space is a good laboratory for determining what role gravity plays in certain basic life processes. These experiments contribute significantly to our understanding of life as well as to the fundamental bank of biological and medical knowledge.

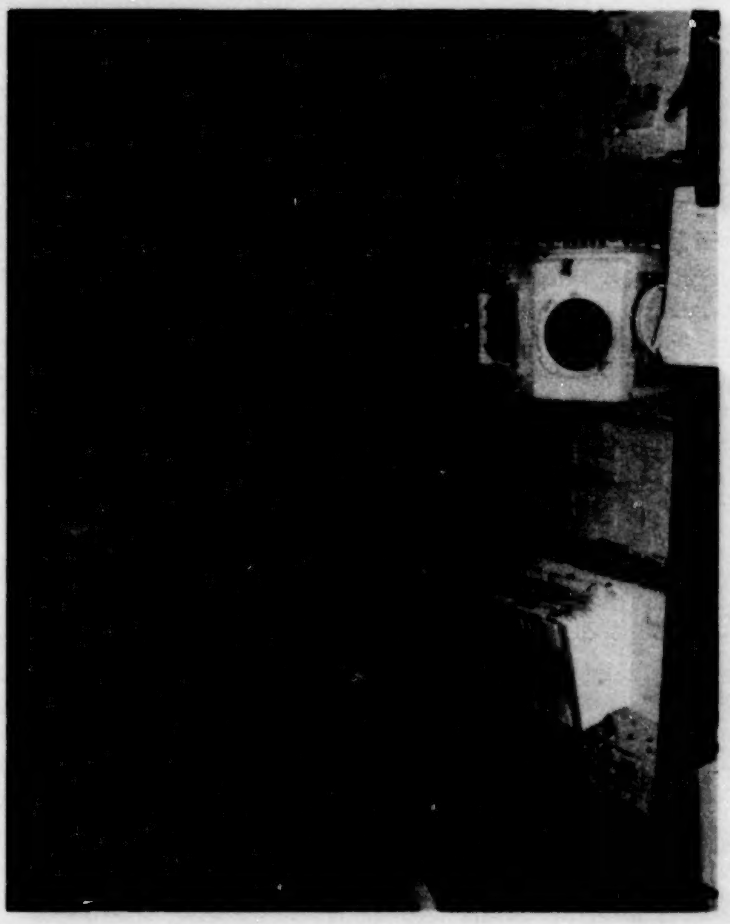
Cellular Functions: The functions and processes of single cells as well as transactions between cells often lead to changes on a larger scale in an organism. This was evident in the white blood cell experiments described earlier, which suggested that responses by these cells to microgravity may alter the human immune system's ability to fight infection. Even the study of the simplest life forms such as bacteria can demonstrate how cells respond to microgravity and other conditions of the space environment. Spacelab is ideally suited for cellular studies because samples are small enough to be observed and manipulated in relatively large numbers, and they can be preserved and returned to Earth for detailed analysis.

The Spacelab D1 Biorack experiments have provided striking evidence of the effects of gravity on bacteria, unicellular organisms, and white blood cells. Fourteen cell and developmental biology experiments were carried aboard the Biorack, a reusable facility equipped with incubators, coolers/freezers, and a glovebox for safely preserving specimens in orbit. The D1 mission was the first Spacelab mission in which specimens were "fixed" in orbit; this fixation allows specimens to be preserved while they are under the influence of microgravity and eliminates influences such as accelerations during landing and adaptation upon return to Earth. To further isolate the effects of microgravity from other space conditions (radiation, vibrations, launch, and landing), most of the D1 experiments used controls in 1-g centrifuges that simulate terrestrial gravity; thus, effects seen in microgravity specimens that are not seen in 1-g specimens may be more strongly linked to gravity.

Several Spacelab D1 experiments studied bacteria, the simplest life form on Earth. Under favorable conditions, these single-celled organisms, not much more than one thousandth of a millimeter in length, reproduce rapidly by repeated cell divisions. This rapid reproduction makes bacteria excellent for studying cell development and proliferation.

Two Biorack experiments confirmed an observation made on several previous flights: bacteria reproduce more rapidly in space. This finding suggests that in space humans may be exposed to greater risks of infection. This additional risk also is suggested by another D1 experiment with *E. coli*, a common pathogenic organism. Under microgravity conditions, the bacteria showed an increased resistance to antibiotics.

The fact that microgravity seems to influence bacteria reproduction also may prove useful. Some bacteria have a primitive form of sexual behavior in which two cells exchange genetic mate-



Cell cultures and other samples on Spacelab D1 were carried in the European Space Agency (ESA) Biorack.

rial through a physical bridge between them. A laboratory technique derived from this phenomenon can be used to introduce human genes – for example, genes needed for insulin production – into bacteria that then can synthesize a useful product. A Spacelab D1 experiment showed that this transfer of genes can occur three to four times faster in microgravity than in 1-g; in space, bacteria may be able to produce biological products more rapidly.

Cell differentiation, the process by which originally similar cells acquire different capabilities, was studied aboard Spacelab. In higher organisms, this process leads not only to the production of cells as different as skin and nerve cells but also to the production of cancer cells from normal cells.

Under certain conditions, many bacteria become dormant by forming spores, which are genetically identical to the active form but function differently. This makes sporulation a simple model for studying cell differentiation. A Spacelab D1 experiment observed a reduction in sporulation and thus differentiation for bacteria. However, the 1-g centrifuge control for this experiment failed, and therefore the experiment needs to be repeated to determine whether the reduction was due to microgravity or other space conditions.

Many organisms other than bacteria consist of single cells, but the cells are much larger (10 to 100 times the size of bacteria) and more complex, possessing a variety of internal structures that perform most of the functions of the organs of higher animals and plants. Like bacteria, many of these organisms proliferate via repeated cell division. Two experiments, one with paramecia and one with green algae, revealed that, as with bacteria, microgravity increased the rate of cell proliferation. In microgravity, the paramecia increased four times faster than the controls. The investigator hypothesized that since the paramecium is a swimming cell, it may use less energy for movement in microgravity and use the extra energy for other activities such as cell proliferation.

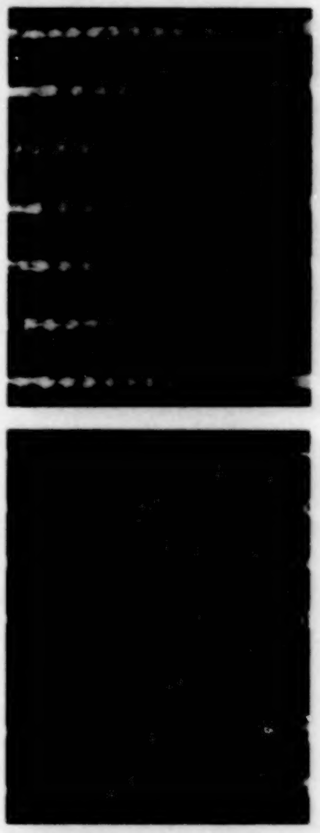
Developmental Processes: Microgravity may affect the development of life from embryo to adult. One Biorack experiment with the much-studied fruit fly revealed that microgravity reduced the rate of development of eggs to 10 percent of the normal rate. Surprisingly, the total number of eggs laid was higher, but the hatching and development rates were reduced. The lifetime of each fly also was measured. While the female flies had the same life span as the control groups, the life span of the male flies was reduced by one-third. This phenomenon needs to be studied more to determine whether shorter lives may be related to the general speeding-up of vital processes observed in unicellular organisms.

Development also seemed to be inhibited in stick insect eggs. During development, this insect passes through several stages differing in radiation sensitivity. Layers of eggs at five different stages of development were sandwiched between radiation detectors so that investigators could detect heavy ions of high energy and charge as they penetrated an egg. This allowed investigators to study the effects of microgravity and radiation on development.

The response to the spaceflight environment varied depending on the stage of development of the eggs. When eggs at late stages of development were hit by a radiation particle, they tended to develop normally. However, a significant reduction or delayed hatching occurred in eggs that were in an early developmental stage when hit by a particle. Development was impaired to a lesser extent in those eggs that were developed in microgravity but were not hit by a particle. Hatching was normal for both hit and non-hit eggs on the 1-g centrifuge, indicating a difference in radiation response depending on gravity environment. During development of the larvae, additional damage – such as reduced life span and increased body abnormalities – was observed in individuals hatched from radiation-exposed eggs in the microgravity samples.

Another experiment studied the development of the vestibular system in tadpoles hatched in space. On Earth, most species develop organs to orient themselves in a gravitational field and coordinate movements. Tadpoles hatched from frog embryos flown aboard the Spacelab D1 mission showed pronounced alteration in swimming behavior upon return to Earth. They swam in small circles around fixed centers until their behavior normalized two days after landing. Later examination of the morphology of the tadpoles' vestibular gravity receptors revealed no structural deformities, indicating that the vestibular system developed normally for the embryos in space. These results correspond with earlier experiments on amphibians and rodents.

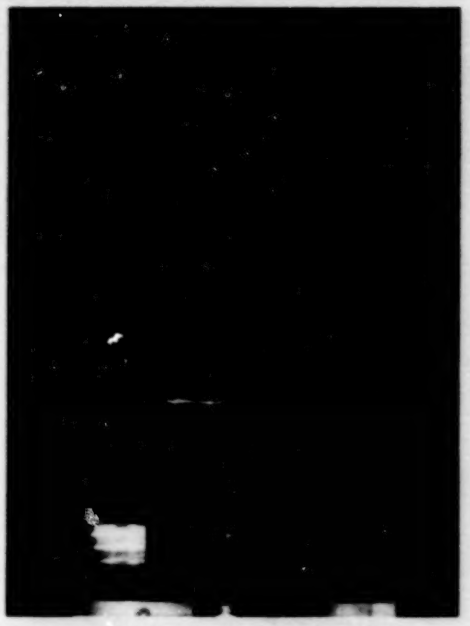
Circadian Rhythms: On Earth, most organisms have behavior patterns that correspond to 24-hour cycles. Debate continues over whether these circadian rhythms are regulated by internal biological clocks or by outside influences such as day-night cycles, seasonal changes, gravity, or the Earth's rotation. For a spacecraft orbiting Earth, there are 16 sunrises and sunsets in a 24-hour period, the Earth's rotation and seasons are eliminated, and there is virtually no gravity. This gives scientists the opportunity to examine circadian rhythms in the absence of normal external cues.



The ten distinct bands seen in each tube of neurospora grown on Earth (a) are evidence of circadian rhythms. The pattern of spaceflight cultures (b) is visibly different from the cultures grown on Earth. The clarity of banding in the spaceflight cultures is reduced, but banding patterns are clearer near the right end of each tube where growth occurred after the tubes were exposed to light. These results suggest that circadian rhythms persist in space but may be altered.

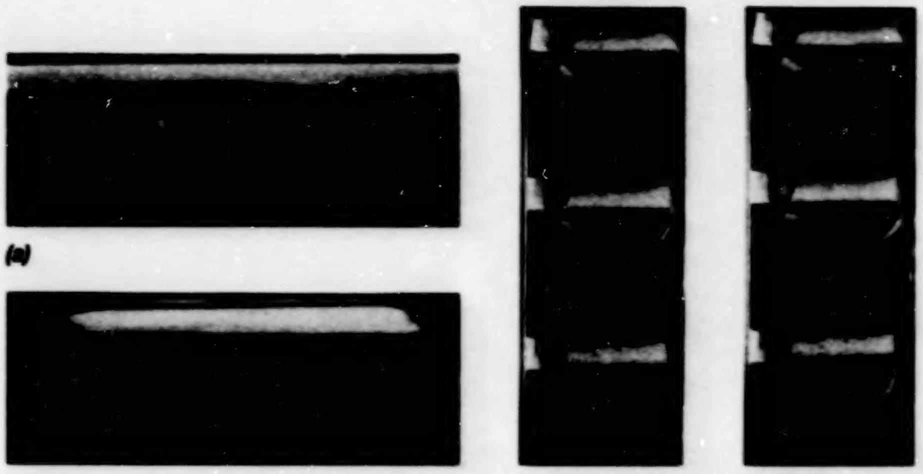
During Spacelab 1, the biological clock theory was tested by examining growth patterns of neurospora, a common fungus. If cultures of neurospora are transferred from constant light to constant darkness, a distinct banded growth pattern is evident that indicates when vegetative spore formation occurs. This experiment produced some confusing but interesting results. The pattern of cultures grown in space was visibly different from the cultures grown on Earth. Growth rates and circadian rhythms varied among the seven cultures grown in space, and the clarity of the banding pattern was reduced. However, after the cultures were moved for marking and exposed to light, robust rhythms were evident in all the sample tubes. The clear pattern seen in all cultures after the tubes were marked proves that the rhythm can persist in space. The damping out of the pattern during the first 7 days of the mission indicates that outside factors probably do influence the biological clock's expression.

Two Spacelab D1 experiments confirmed the observation that the clock works in a low-gravity environment free of terrestrial signals. In an experiment with green algae, the algae continued to display patterns in a specific rhythm while in microgravity; however, unlike the Spacelab 1 neurospora, the patterns were more prominent in low gravity and damped out more slowly. In another experiment, investigators recorded the movements of a single-celled slime mold that moves with regularly timed oscillations on Earth. In space, the protoplasm of the slime mold moved with the same biological periodicities, indicating the operation of the biological clock, but the behavior was somewhat altered with the velocity of the protoplasm increasing in microgravity.



Pine seedlings grown in microgravity had less lignin, a structural fiber that helps plants grow upright in spite of gravity. Some plants may be more useful as food and industrial products if their lignin content can be reduced.

Plants: From preliminary Shuttle/Spacelab experiments, biologists have learned about the fundamental behavior of plants and how to grow and maintain them in orbit. Sunflowers were the first plant to be flown aboard the Shuttle; on STS-2 and STS-3, sunflowers were grown to test a new plant growth apparatus and at the same time


(a) (b) (c) (d)

Lentil roots grown in microgravity (a) were oriented randomly, whereas roots grown in space on a 1-g centrifuge (b) grew in the direction of acceleration. Roots grown in microgravity (c) were disoriented but did not seem to lose their ability to perceive gravity because when placed on a 1-g centrifuge (d), they grew in the direction of accelerations that simulated gravity.

confirm that water delivery to plants is basically the same in microgravity as on Earth.

For the Spacelab 1 mission, sunflowers were studied again to resolve a question about a peculiar circular growth movement called nutation. As plants grow on Earth, their tips describe a helix around a central axis. Plant physiologists have wondered whether this movement depends on gravity or on an internal growth mechanism. Theories predicted that nutation would virtually cease in microgravity. During Spacelab 1, plants were observed by time-lapse video, and the nutation proceeded. Although the nutation of the microgravity plants varied somewhat from the ground controls, the fact that nutation occurred suggests that the response is influenced by other mechanisms rather than triggered by gravity alone.

Plant experiments with mung beans, oats, and pine seedlings were conducted on two Shuttle flights (STS-3 and Spacelab 2). These experiments studied the ability of plants to synthesize lignin, a structural fiber that plants use to grow upright against gravitational force. Lignin, though useful for rigidity, is difficult to digest and is detrimental in some industrial processes such as making paper. Scientists think that if lignin content could be reduced in some plants, the plants would make better food and industrial products.

During the STS-3 mission, pine seedlings and oats grown on the Shuttle showed no significant decrease in lignin, but mung beans had an average 18 percent less lignin than ground controls. When the experiment was modified slightly and repeated aboard Spacelab 2 with oats, mung beans, and some more mature pine seedlings, all three species showed significant reduction in lignification. For the pine seedlings and mung beans, there was a decrease in enzymes associated with lignin synthesis as well as a slight overall growth reduction for the stems and leaves. To see if this trend continues or is enhanced with plant development, this experiment should be repeated with more mature plants.

Interesting plant behavior was also observed: many of the mung beans and oats had roots emerging upward out of the soil. This indicates that, in the absence of gravity, plant growth may be disoriented. The mechanism by which plants know which way to grow is still a matter of controversy. In a Spacelab D1 experiment, lentil seeds were germinated in microgravity and on a 1-g centrifuge. The microgravity-grown roots grew down into the soil but were not oriented correctly. However, the plants demonstrated that the ability to sense gravity-like accelerations was not permanently lost. When placed on a 1-g centrifuge, the plants oriented their roots in alignment with the accelerations.

For maximum benefit, tissues from the sunflowers, oats, and mung beans were shared with other scientists for some interesting genetic and structural studies. Chromosomal studies of the sunflower and oat root tips showed several abnormal chromosomes and depressed cell division. Plants grown on the ground had twice as many cells in division as the plants grown in flight. The oats had broken and fractured chromosomes more severe than any in ground controls. These results indicate that microgravity and/or other spaceflight conditions, such as radiation, may damage the cell's genetic material.

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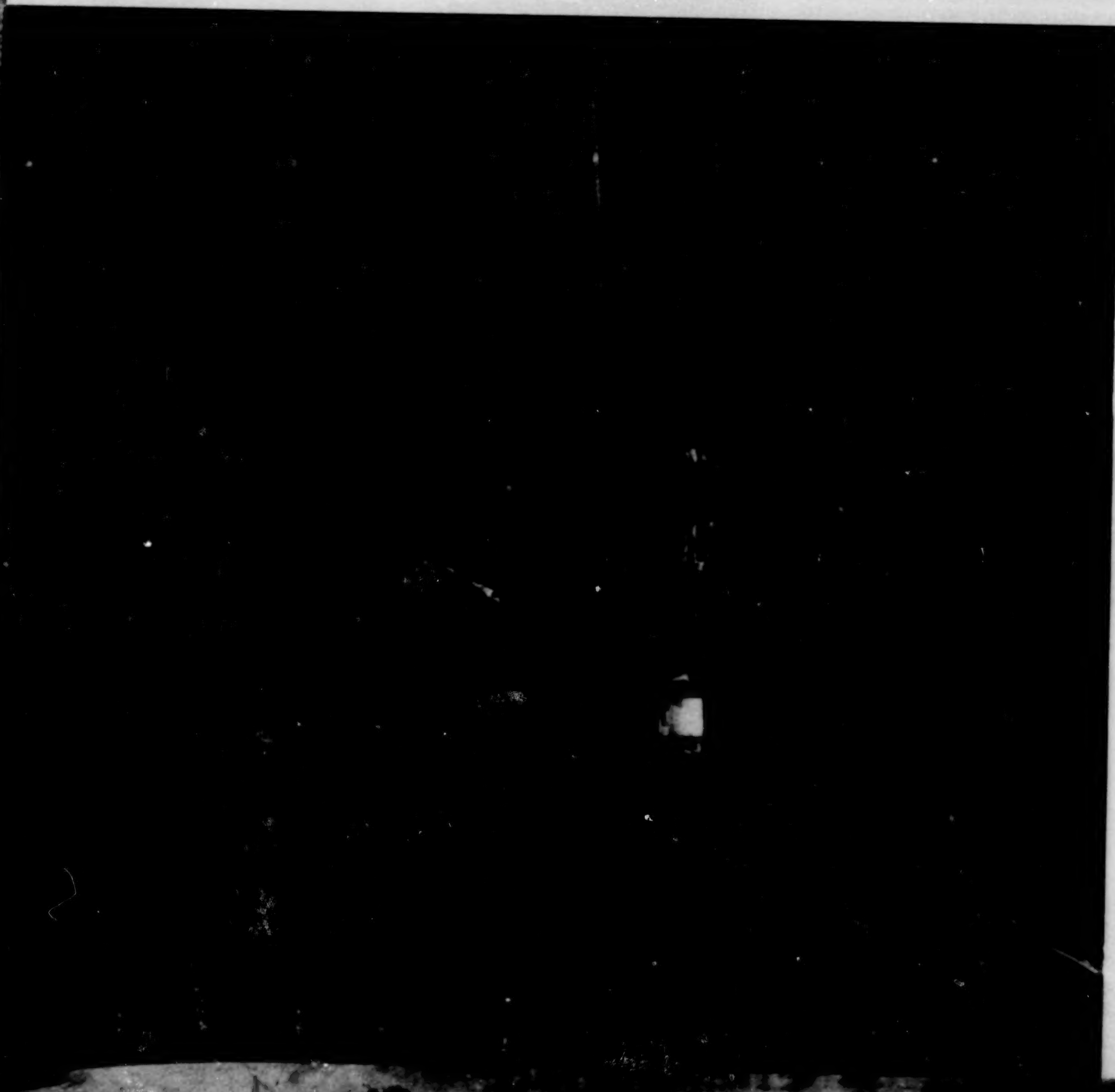
The Space Environment: Other aspects of the space environment such as high radiation and vacuum affect life in space. The hazardous environment of space includes unfiltered ultraviolet radiation, X-rays, gamma rays, and high-energy particles (electrons, neutrons, protons, and heavy ions) that do not reach Earth's surface because they are either deflected by the geomagnetic field or absorbed in the atmosphere. Heavy particles with high energies and charges (HZEs), which are relatively rare but very penetrating and damaging, are of special interest because they are poorly understood and can penetrate spacecraft shielding.

To measure radiation effects on living organisms, a Spacelab 1 experiment used biostacks, single layers of organisms sandwiched between thin foils of nuclear track detectors. A vari-



Because astronauts work outside to service satellites and build space structures, it is important to characterize radiation levels under varying conditions.

ety of organisms that differed in size, position in the stack, organizational level, developmental stage, and radiation sensitivity were flown. These included single cells, developing eggs, spores, and seeds. Some biostacks were placed inside the Spacelab module and others were directly exposed to space on the pallet. By comparing the tracks of high-energy particles on the detectors with the biological samples through which they passed, investigators could correlate the effect of radiation on a single cell. Results indicate that single high-energy particles can induce dramatic changes in individual cells, such as genetic damage and death.

A related Spacelab D1 experiment with stick insect eggs sandwiched between biostack particle detectors indicated that the HZE particles produced different degrees of damage at various development stages. Interestingly, the effects of the radiation were enhanced in eggs exposed to microgravity and less damaging in eggs kept on a 1-g centrifuge.

In other radiation measurements, several detectors both inside and outside the Spacelab 1 module measured doses of radiation three times higher than those measured during other Shuttle missions. Although the radiation dose was relatively benign and did not endanger the crew, investigators attributed the higher radiation level to the higher inclination orbit. (Spacelab 1 was the first mission with a 57 degree inclination rather than the 28 to 40 degree orbits for previous missions.) Scientists had predicted that there would be higher electromagnetic and particle radiation fluxes at higher inclination orbits. Further study is warranted before we embark on long-term missions at higher altitudes and inclinations.

The effects of vacuum and ultraviolet radiation were also studied on Spacelab 1. Spores exposed outside on the pallet formed 50 percent fewer colonies and had 10 times more mutations than samples grown under normal atmospheric conditions.

Biological Processing In Space:

Life sciences research not only prepares us to live and work in space but also may improve life on Earth. Bioprocessing in space is a new discipline of growing importance. It is closely related to understanding how cells function in gravity since many of these cells make useful products. Early experiments have focused on developing the apparatus and techniques for processing biological substances.

Protein crystal growth in space has been especially interesting because of the potential applications for determining the three-dimensional structure of proteins. Many of the molecules essential for living organisms – especially proteins and nucleic acids – have extremely complicated three-dimensional structures, many of which are unknown. To decipher these structures, crystallographers coax biological molecules to organize symmetrically into crystals big enough to study and then bombard the crystals with X-rays to create patterns which computers can analyze.

Molecular biologists need this information to understand the complex functioning and interrelationships among biological materials and organisms. Knowing the exact architecture of hormones, enzymes, and other proteins enables scientists to bypass years of tedious trial-and-error experimentation in efforts to design new and more effective drugs and to produce improved synthetic proteins for industrial applications.

Currently, X-ray crystallography is the only technique available for elucidating the atomic arrangements within complicated biological molecules, and this method requires well-formed, large, single crystals of the compounds being studied. On Earth, convection and turbulence during crystal formation disrupt the internal crystalline structure, and sedimentation causes crystals to clump together instead of forming distinctly. One of the great bottlenecks in protein crystallography has been the inability to produce large, pure crystals for analysis.

Fortunately, experiments aboard the Shuttle and Spacelab missions indicate that much larger and higher quality crystals can be grown in space where microgravity inhibits convection and crystals float freely in solution rather than clump together. In a Spacelab 1 experiment, two enzymes were crystallized: beta-galactosidase (a key genetic ingredient) and lysozyme (a basic protein that is well-studied). In both cases, the crystals grown in orbit were much larger and purer than those grown in the same apparatus on the ground.

This successful experiment sparked a united effort by a team of scientists who developed an apparatus for growing protein crystals in space. Protein crystals have been grown on four Shuttle flights by a vapor diffusion technique. During the most recent

experiments aboard the 61-C mission, crystals were grown of these proteins: lysozyme, a protein from hen egg white with a well-known structure that can be used to compare the quality of ground- and space-grown crystals; bacterial purine nucleoside phosphorylase (PNP), a protein (with an unknown structure) used for synthesis of anti-cancer drugs; human C-reactive protein (CRP), a major component of the human immune system; human serum albumin, a protein known to bind and transport a number of important biological molecules as well as certain drugs; and canavalin and concanavalin B, two proteins that have well-known structures for modeling and are of interest in protein engineering to improve the nutritional value of food sources.

Many of the space crystals were larger than any previously grown on the ground, and some formed into distinct crystals rather than small, attached crystals. In the case of human C-reactive protein, a crystal form that had not previously been identified in ground-based experiments was obtained first aboard the Shuttle and has since been produced on the ground. The internal structures of some of the space crystals appear to be more ordered; however, before this can be thoroughly assessed, more detailed comparisons with large numbers of crystals grown under well-controlled conditions on Earth and in space are necessary. Based on these preliminary results, a larger protein crystal growth facility with a more controlled environment is being developed for future missions.

Materials scientists and biologists are collaborating on other projects, including the Continuous Flow Electrophoresis System (CFES) project which is a joint endeavor between NASA and private industry. The objective of this program is to separate and purify biological substances for pharmaceutical purposes. Substances processed on several Shuttle flights are currently being evaluated by a pharmaceutical company.

Expanding in Space: Even though we have more than a quarter century of manned spaceflight experience, fundamental questions remain about the immediate and long-term effects of space on humans and other organisms. As we experiment in space, we answer some questions but are left with more "unknowns." The Shuttle and Spacelab experiments have been pathfinders, addressing important questions, developing equipment and techniques for research, and leading to discoveries impossible to detect in the gravitational environment on Earth. There are still many life sciences experiments waiting for sorties aboard the Shuttle/Spacelab, while others are being developed for long-term stays aboard the Space Station.

The data obtained so far indicate a

These crystals of purine nucleoside phosphorylase (PNP) grown in space are large enough to analyze by X-ray crystallography.

If the structure of PNP (shown in this computer model) can be defined, the information may help in designing anti-cancer drugs.

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fascinating pattern: all living organisms from microbe to man are influenced by gravity. It is built into our very cells, tissues, and organs in myriad overt and subtle ways. Discrete experiments flown aboard the Shuttle can be integrated aboard the Space Station so that scientists can collaborate to study organisms as a whole and determine how gravity influences an organism through its entire life and in subsequent offspring.

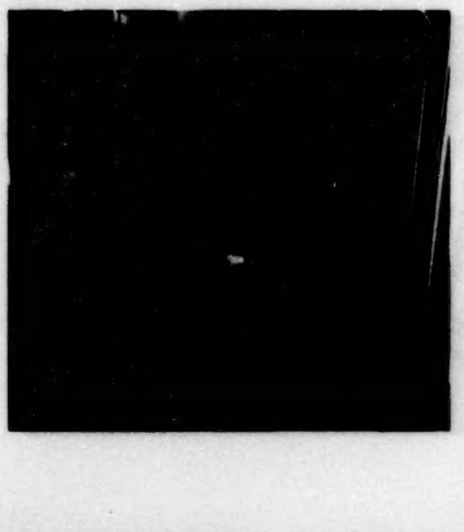
Aboard the Space Station, life scientists will team up with materials scientists, Earth scientists, and astrophysicists to explore life from the micro to macro level. Materials scientists will develop better protein crystals and purer biological specimens, which life scientists can analyze to determine the structure of life.

With photographs and infrared maps from Earth-orbiting platforms and satellites, biologists can understand the interaction of Earth and its environment on a global scale. They can correlate biological, geological, chemical, and oceanographic data to determine how changes (increased industrialization, land clearing, oil spills, etc.) propagate to neighboring areas in the biosphere.

Before long-term space missions, many aspects of human physiology and psychology must be examined. A Spacelab 1 experiment studied the payload specialists' abilities to estimate varied masses in microgravity.

The Space Station will offer life scientists, chemists, and astrophysicists a chance to do unique experiments in exobiology, the study of the origin, evolution, and distribution of life in the universe. Astronomers already have detected the essential biochemicals (carbon, nitrogen, oxygen, phosphorus, sulfur, etc.) light-years away from Earth. The Space Station will have an unobstructed view of the solar system, comets, meteorites, and asteroids which may contain molecules and chemical fragments of biological significance. Continuous viewing of the universe from the Station and orbital observatories increases our chances of finding other planets and perhaps other life in the universe. The Station can be used as a platform for huge cosmic dust collectors, allowing biologists to examine particles from interstellar space for biogenic elements and maybe even simple organisms.

The study of life in our solar system will be augmented by manned and unmanned planetary expeditions. Through NASA's Controlled Ecological Life Support System (CELSS) program, scientists are working to develop life support systems for spacecraft that can process wastes, recycle air and water, and support the cultivation of plant and animal food sources. This type of spacecraft, which will be used for long-duration missions where resupply from Earth is impractical or impossible, will make deep space accessible to human exploration.



Biologist crewmembers practice experiments for future life sciences missions.

Space must be a comfortable and productive workplace. We are still largely ignorant of the mechanisms and limits of human adaptation to prolonged spaceflight. Scientists must determine how humans and other organisms adapt to the space environment and develop sound countermeasures to detrimental effects. Human factors and physiological experiments will be conducted to design the Space Station as well as other space workstations for safety, efficiency, and comfort.

There is still much to be accomplished before space becomes our home and workplace. The Shuttle will continue to be a testbed for advanced equipment. A series of dedicated Spacelab Life Sciences (SLS) missions staffed by expert biologists is already planned for the next decade. By dedicating a mission to one discipline, it is possible to integrate experiments and explore a spectrum of related data. A series of International Microgravity Laboratory (IML) missions shared by materials and life scientists will carry valuable experiments and has already enabled an international working group of scientists to establish a solid base for sharing ideas and results.

Results from the Shuttle and Spacelab missions have blazed the paths of exploration, and we are beginning to make space an extension of life on Earth. ■

Life Sciences Investigations

OSTA-1/STS-2
- Heflex Bioengineering Test I
  A.H. Brown, University of Pennsylvania
  Philadelphia, Pennsylvania

OSS-1/STS-3
- Heflex Bioengineering Test II
  A.H. Brown, University of Pennsylvania
  Philadelphia, Pennsylvania
- Influence of Weightlessness on Lignification in Plant Seedlings
  J.R. Cowles, University of Houston, Texas

Spacelab 1/STS-9
- Advanced Biostack Experiment
  H. Bücker, DFVLR, Cologne, West Germany
- Circadian Rhythms during Spaceflight: Neurospora
  F.M. Sulzman, NASA Headquarters
  Washington, D.C.
- Effect of Weightlessness on Lymphocyte Proliferation
  A. Cogoli, Swiss Federal Institute of Technology
  Zurich, Switzerland
- Humoral Immune Response
  E.W. Voss, University of Illinois
  Urbana, Illinois
- Influence of Spaceflight on Erythrokinetics in Man
  C.S. Leach, NASA Johnson Space Center
  Houston, Texas
- Mass Discrimination during Weightlessness
  H.E. Ross, University of Stirling, Scotland
- Measurement of Central Venous Pressure and Hormones in Blood Serum during Weightlessness
  K. Kirsch, Free University of Berlin, West Germany
- Microorganisms and Biomolecules in the Space Environment
  G. Horneck, DFVLR, Cologne, West Germany
- Nutation of Sunflower Seedlings in Microgravity*
  A.H. Brown, University of Pennsylvania
  Philadelphia, Pennsylvania
- Personal Electrophysiological Tape Recorder
  H. Green, Clinical Research Center, Harrow, England
- Crystal Growth of Proteins
  W. Littke, University of Freiburg, West Germany
- Radiation Environment Mapping
  E.V. Benton, University of San Francisco, California
- Rectilinear Accelerations, Optokinetic and Caloric Stimulations
  R. von Baumgarten, University of Mainz, West Germany
- Three-Dimensional Ballistocardiography in Weightlessness
  A. Scano, University of Rome, Italy
- Vestibular Experiments
  L.R. Young, Massachusetts Institute of Technology
  Cambridge, Massachusetts
- Vestibulo-Spinal Reflex Mechanisms
  M.F. Reschke, NASA Johnson Space Center
  Houston, Texas

OSTA-3/41-G
- National Research Council of Canada Vestibular Investigations
  D. Watt, McGill University, Montreal, Canada

Spacelab 3/51-B
- Autogenic Feedback Training
  P.S. Cowings, NASA Ames Research Center
  Moffett Field, California
- Research Animal Holding Facilities
  P. Callahan and C. Schatte, NASA Ames Research Center
  Moffett Field, California
- Urine Monitoring Investigation
  H. Schneider, NASA Johnson Space Center, Houston, Texas

51-C
- Aggregation of Human Red Blood Cells
  L. Dintenfass, Kanematsu Institute, University of Sidney, Australia

51-D

- American Flight Echocardiograph
  M.W. Bungo, NASA Johnson Space Center
  Houston, Texas
- Continuous Flow Electrophoresis System**
  D. Clifford, McDonnell Douglas Aerospace Company
  St. Louis, Missouri
- Protein Crystal Growth Experiment
  C.E. Bugg, University of Alabama in Birmingham, Alabama

Spacelab 2/51-F

- Gravity Influenced Lignification in Higher Plants*
  J.R. Cowles, University of Houston, Texas
- Protein Crystal Growth Experiment*
  C.E. Bugg, University of Alabama in Birmingham, Alabama
- Vitamin D Metabolites and Bone Demineralization
  H.K. Schnoes, University of Wisconsin
  Madison, Wisconsin

51-G

- French Echocardiograph Experiment
  L. Pourcelot, University of Tours, France
- French Postural Experiment
  A. Berthoz, National Center for Scientific Research, Paris, France

51-J

- BIOS
  S.L. Bonting, University of Nijmegen, The Netherlands

Spacelab D1/61-A

- Antibacterial Activity of Antibiotics in Space Conditions
  R. Tixador, University of Toulouse, France
- Body Impedance Measurement
  F. Baisch, DFVLR, Cologne, West Germany
- Cell Cycle and Protoplasmic Streaming
  V. Sobick, DFVLR, Cologne, West Germany
- Cell Growth and Differentiation in Space
  H.D. Mennigmann, University of Frankfurt, West Germany
- Cell Proliferation
  H. Planel, University of Toulouse, France
- Central Venous Pressure*
  K. Kirsch, Free University of Berlin, West Germany
- Circadian Rhythm under Conditions Free of Earth Gravity
  D. Mergenhagen, University of Hamburg, West Germany
- Determination of the Dorsoventral Axis in Developing Embryos of the Amphibian
  G.A. Ubbels, University of Utrecht, The Netherlands
- Determination of Reaction Time
  M. Hoschek and J. Hund, DFVLR, Cologne, West Germany
- Differentiation of Plant Cells
  R.R. Theimer, University of Munich, West Germany
- Distribution of Cytoplasmic Determinants
  R. Marco, University of Autonoma, Madrid, Spain
- Dosimetric Mapping Inside Biorack
  H. Bücker, DFVLR, Cologne, West Germany
- Effect of Microgravity on Interaction between Cells
  O. Ciferri, University of Pavia, Italy
- Embryogenesis and Organogenesis under Spaceflight Conditions
  H. Bücker, DFVLR, Cologne, West Germany
- Frog Statoliths
  J. Neubert, DFVLR, Cologne, West Germany
- Geotropism
  J. Gross, University of Tubingen, West Germany
- Gesture and Speech in Microgravity
  A.D. Friederici, University of Nijmegen, The Netherlands
- Graviperception of Plants
  D. Volkmann, University of Bonn, West Germany
- Human Lymphocyte Activation*
  A. Cogoli, Swiss Federal Institute of Technology
  Zurich, Switzerland
- Mammalian Cell Polarization
  M. Bouteille, University of Paris, France
- Mass Discrimination in Weightlessness*
  H.E. Ross, University of Stirling, Scotland
- Protein Crystals*
  W. Littke, University of Freiburg, West Germany
- Spatial Description in Space
  A.D. Friederici, University of Nijmegen, The Netherlands
- Statocyte Polarity and Geotropic Response
  G. Perbal, University of Paris, France
- Tonometer
  J. Draeger, University of Hamburg, West Germany
- Vestibular Research
  L.R. Young, Massachusetts Institute of Technology
  Cambridge, Massachusetts
- Vestibular Research
  R. von Baumgarten, University of Mainz, West Germany

61-B

- Continuous Flow Electrophoresis System**
  D. Clifford, McDonnell Douglas Aerospace Company
  St. Louis, Missouri
- Effects of Weightlessness and Light on Seed Germination
  A.J. Peluyera, National Consumer Institute, Mexico City, Mexico
- Electropuncture in Space
  F. Ramirez y Escalano, Mexico
- Protein Crystal Growth Experiment*
  C.E. Bugg, University of Alabama in Birmingham, Alabama
- Transportation of Nutrients in a Weightlessness Environment
  I. Ortega, Institute of Physics, Cuernavaca, Mexico

61-C

- Noninvasive Estimation of Central Venous Pressure Using a Compact Doppler Ultrasound System
  J.B. Charles and M.W. Bungo, NASA Johnson Space Center
  Houston, Texas
- Protein Crystal Growth Experiment*
  C.E. Bugg, University of Alabama in Birmingham, Alabama

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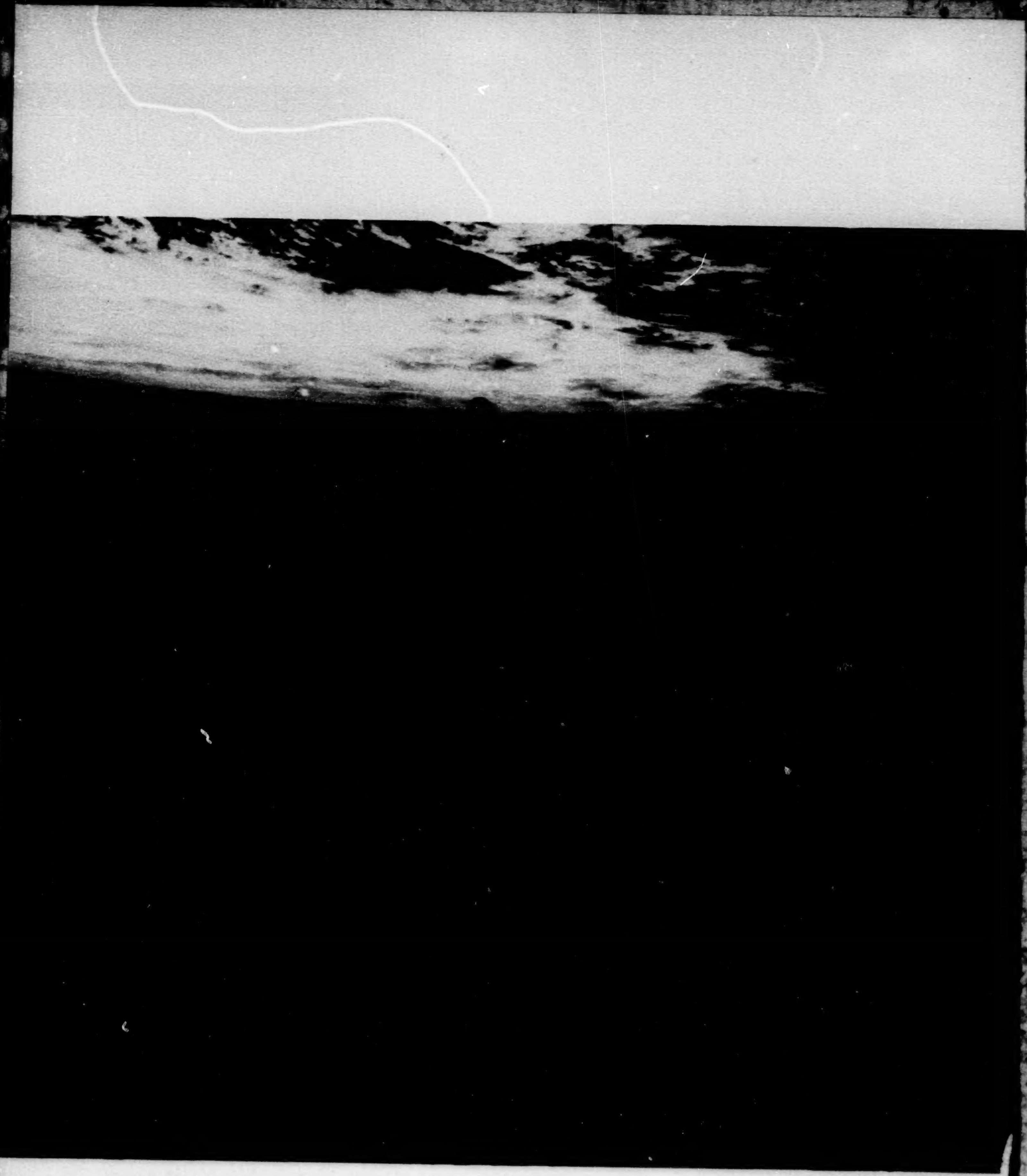
* Reflight
** 6 missions completed (STS-6, -7, -8, 41-D, 51-D, 61-B)



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Chapter 3

Studying Materials and Processes in Microgravity: Materials Science

Materials science includes such diverse processes as converting sand to silicon crystals for use in semiconductors, producing high-strength, temperature-resistant alloys and ceramics, separating biological materials into valuable drugs and chemicals, and studying the basic phenomena that influence these processes. Materials processing is melting, molding, crystallizing, and combining or separating raw materials into useful products. The history of science and civilization goes hand in hand with advances in materials science and technology.

In some cases, progress in materials science on Earth has been limited: materials will not mix to form new alloys; crystals have defects that limit their performance; biological materials cannot be separated well enough to form some ultra-pure substances needed for medicine; crystals clump together instead of forming distinctly; glasses are contaminated by processing containers. Many of these problems are related to a constant force on Earth — gravity.

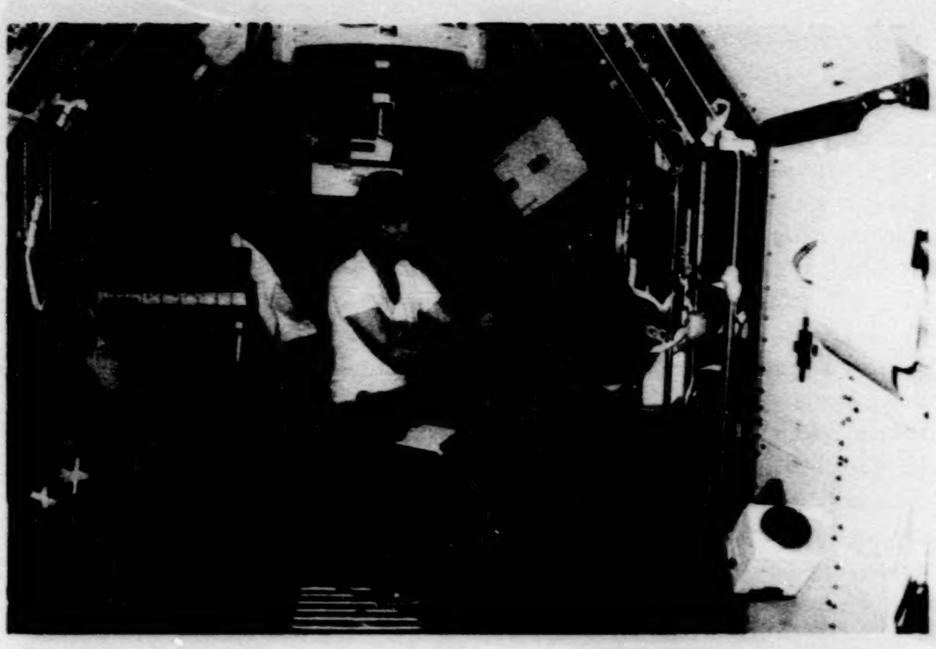
The presence of gravity has been counteracted in low-gravity aircraft flights and drop tubes, which offer about 30 seconds and 4 seconds of microgravity, respectively. Although the period of microgravity is brief, these test facilities are beneficial for research in preparation for spaceflight. The pull of gravity cannot be escaped at any altitude; at a 322 kilometer (200 mile) orbit, it is still 90 percent as strong as at the Earth's surface. However, its effects can be virtually cancelled by remaining in "free fall," that is, by remaining in orbit around the Earth as a satellite does. Spaceflight offers extended periods of low gravity; long duration is important for most solidification experiments, especially crystal growth. It is impossible to sustain a comparable microgravity environment on Earth.

NASA's microgravity science program uses spaceflight to eliminate or counteract gravity-induced problems that hamper materials scientists on the ground: buoyancy-driven convection in liquids, contamination from vessels that contain samples, and induced stresses that cause defects in crystals. Dramatic improvements in material properties have been achieved in recent microgravity experiments as our ability to control temperature has improved. Similar improvements can be expected in the future as our understanding of the effects of mass transport increases along with our ability to control convective flows.

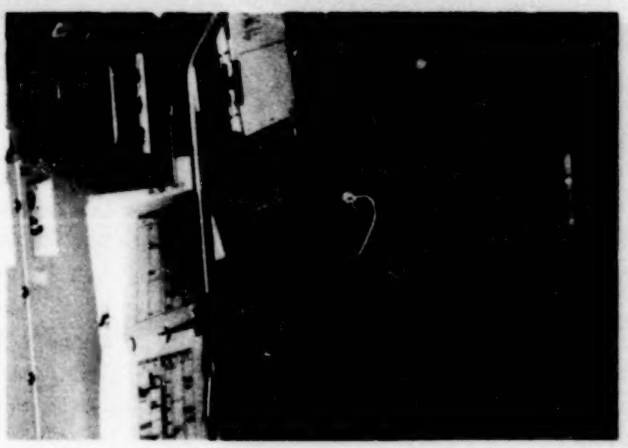
Pioneering experiments from 1969 to 1975 aboard Apollo-era spacecraft and the Skylab space station led the way to microgravity science payloads developed for the Space Shuttle in the late 1970s. The Shuttle/Spacelab has proven useful for carrying many new automated and manually controlled facilities developed for materials science research.

Automated systems are appropriate for simpler experiments that need less crew involvement but still require the return of samples and equipment to the ground for analysis. The automated Materials Experiment Assembly (MEA) combined low-cost sounding rocket techniques with the extended microgravity duration of the Shuttle. This carrier supports three or four experiment modules in the payload bay.

Studying Materials and Processes in Microgravity



Crewmembers on board the Spacelab can continuously monitor and adjust experiments.

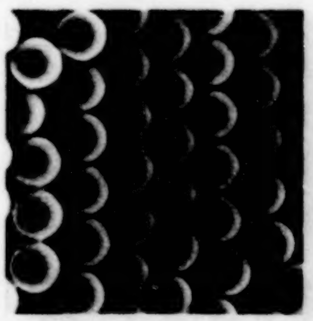


For more sophisticated experiments requiring intense observation and crew control, facilities have been developed for the shirt-sleeve laboratory environment of the Spacelab module and for the Shuttle middeck. Spacelab offers scientists a place to do exploratory work such as attempting new processing techniques or testing basic theories. Scientists serve as crewmembers to observe and control experiments.

Thinking in Terms of Microgravity: Because gravity is a dominating factor on Earth, it is difficult to think in terms of reduced gravity. Results from the early Shuttle/Spacelab missions prove that scientists are meeting this challenge as they develop techniques and attempt experiments that are affected by gravity in laboratories on the ground.

The first space product is now on the market: monodisperse latex spheres, precision microspheres that can be produced in space with improved uniformity. These spheres, which were produced in an apparatus in the Shuttle middeck during five missions, have been recognized as a calibration standard for microscopy.

Many of the experiments accomplished to date are not aimed at production but seek to discover more about the fundamental physics and



Latex spheres processed in space

Latex spheres processed on Earth

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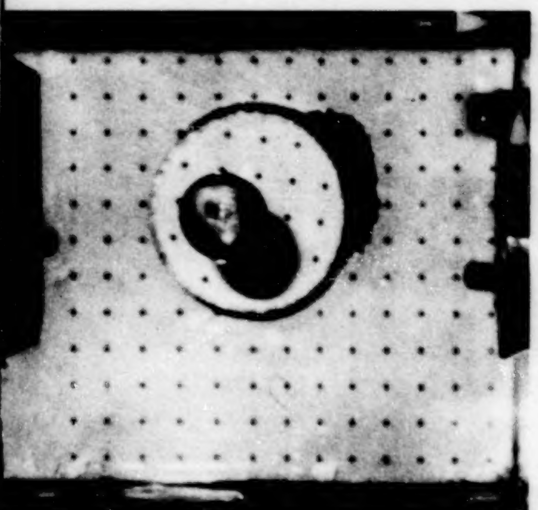
chemistry of materials processes on Earth. In microgravity, space scientists can use techniques to improve measurement accuracy and to try to observe phenomena that are not detectable on Earth. Analyses of samples produced in microgravity allow scientists to determine how gravity affects materials processing. For example, convection and sedimentation dominate the transport of heat and matter in many systems, but in space the effects of weaker forces such as surface tension are unveiled. Clarification of these phenomena may lead to better processing techniques on Earth and result in the discovery of materials with novel and commercially interesting properties.

The types of materials processed aboard the Shuttle/Spacelab include crystals and electronic materials, metal alloys and composites, glasses and ceramics, fluids and chemicals, and biological materials.



Many of the Shuttle/Spacelab experiments examine the fundamental physics influencing all materials processes. A Spacelab 3 payload specialist did experiments on the basic behavior of liquid drops levitated in microgravity.

Crystals and Electronic Materials: Crystals have achieved far greater value as electronic materials than they ever had as gems. Man has improved on nature's offerings but has been halted by bottlenecks that prevent some crystals from reaching their theoretical performance limits. Before crystal growth can be improved, scientists must determine what factors are responsible for crystal defects and learn how to control them.

Striking results were obtained with experiments on mercury iodide, a soft crystal valued for its potential as a nuclear radiation detector because it operates at room temperature without a bulky cooling system. Controlling the growth of a large mercury iodide crystal in microgravity was demonstrated with the Spacelab 3 Vapor Crystal Growth System. For the first time, crewmembers on the Shuttle and scientists on Earth monitored a crystal as it grew in microgravity. Images were relayed to the ground via television, and the crew viewed the crystal through a microscope imaging system. This allowed the growth of the crystal to be tracked through each stage, and scientists changed parameters such as temperature to adjust the growth and reduce defects, much as they do in ground-based laboratories.

A seed crystal mounted on a small, cooled finger (sting) at the base of the ampoule was a condensation point for material evaporated from a source at the top. The crystal grown in space for 100 hours was comparable to the best terrestrial crystals. The crystal quality, seen by reflecting X-rays, appeared to be better than the ground-based crystal used as a standard. Gamma ray tests showed the interior quality to be better than terrestrial mercury iodide crystals.

During the Spacelab 3 mission, more basic knowledge about crystal growth in microgravity was obtained by growing triglycine sulfate (TGS) crystals in the Fluid Experiment System. Triglycine sulfate has potential as an infrared radiation detector at room temperature. This crystal has not met expected standards because, when grown to useful sizes, it develops defects which limit its performance.

For this experiment, TGS crystals were grown from solution with liquid TGS fluid solidifying on a seed crystal. The crystal and fluid are transparent, which makes it possible to record images of fluid motions. The growth chamber was in the center of a precision optical system which allowed photography by three techniques: shadowgraphy; schlieren, by which variations in fluid density make flow

Scientists used video images of a mercury iodide crystal to track its growth and adjust parameters, much as they do in ground-based laboratories.

patterns visible; and interference holography, using lasers to record density variations near the sample.

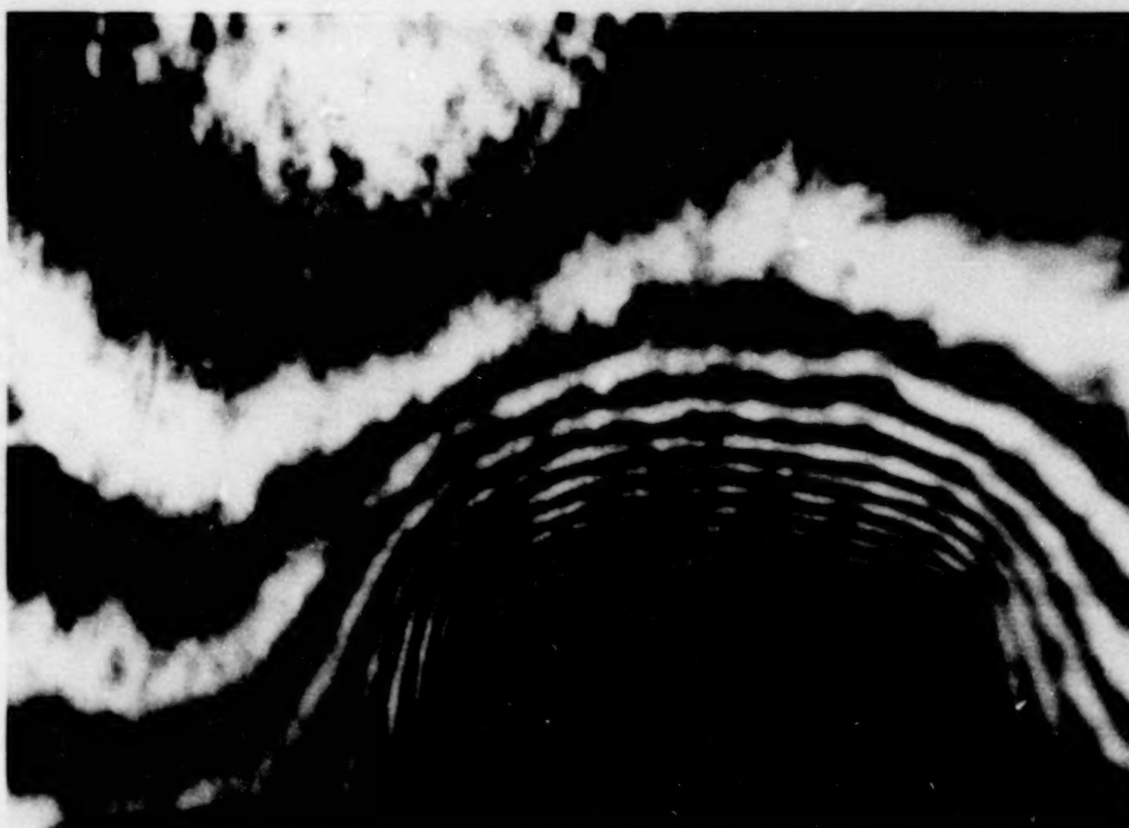
The TGS crystals shed light on how defects are formed and what role convection plays in creating defects, something that is not well understood. At the beginning of growth, a portion of the seed crystal is dissolved to form a smooth growth surface. In Earth-grown crystals, there is always a visible line where the seed crystal stops and the new growth begins; this introduces defects into the crystal. In the space-grown crystals, this line was not detected. This indicates that in the absence of convection the transition is smoother between the seed and the start of new growth.

A Spacelab 1 crystal growth experiment examined insoluble crystals (calcium and lead phosphates) that grow quickly to form plate-like crystals which are easily studied by X-ray techniques. Large crystals were grown, and the portions of the crystals grown in microgravity were free of defects. Defects were evident in portions of the crystals grown as the Shuttle landed, suggesting that defects are reduced in microgravity.

Another Spacelab 1 experiment studied processes linked to the distribution of dopants (trace elements) that give crystals desired electrical properties. For example, the conductivity of semiconductors is dramatically changed by adding dopants. However, nonuniform distribution of these dopants can interfere with the operation of electrical devices that use crystals. For most applications, the semiconductors produced on Earth are adequate, but for some highly specialized applications more uniformly doped, defect-free crystals are needed. Earlier experiments determined that convection that varies over time caused dopant striations in crystals.

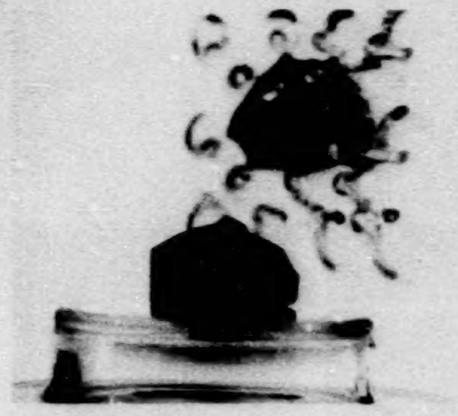
The Mirror Heating Facility (Spacelab 1) modeled float-zone Earth-processing methods to determine whether the troublesome convective flows were produced by buoyancy or surface tension. Two experiments were done in an attempt to grow defect-free, single crystals of silicon. However, the space-grown crystals had the same marked dopant striations seen in Earth-grown crystals, confirming that Marangoni convection (flow driven by surface tension) may be a dominant cause of the defects on Earth and in space.

In ground-based experiments after Spacelab 1, the silicon seed crystal was coated with a thin oxide layer to prevent Marangoni flow as the crystal grew. The striations were eliminated, indicating that this is a successful technique for reducing the effects of Marangoni flow. For Spacelab D1, the experiment was repeated using this technique, and striation-free crystals also were grown in space.



Right: Scientists used this black and white image showing density profiles in the fluid surrounding the triglycine sulfate crystal to generate a color computer map of fluid concentrations.

Far Right: The crystal was growing when this image was made; blue denotes the area near the crystal surface which has the least fluid concentration.



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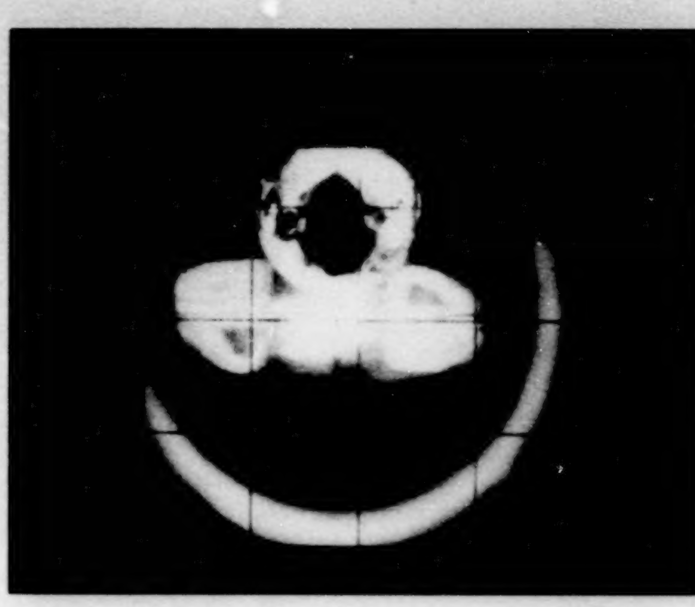
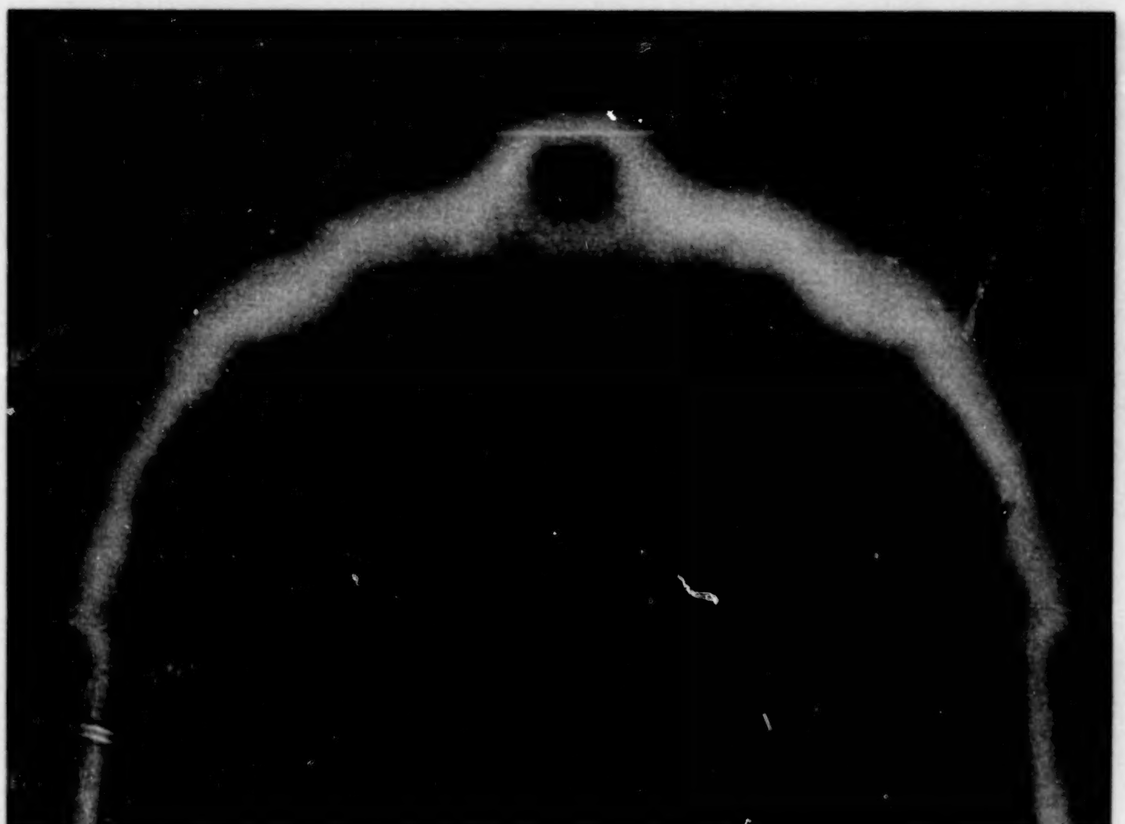
Mercury Iodide Crystal

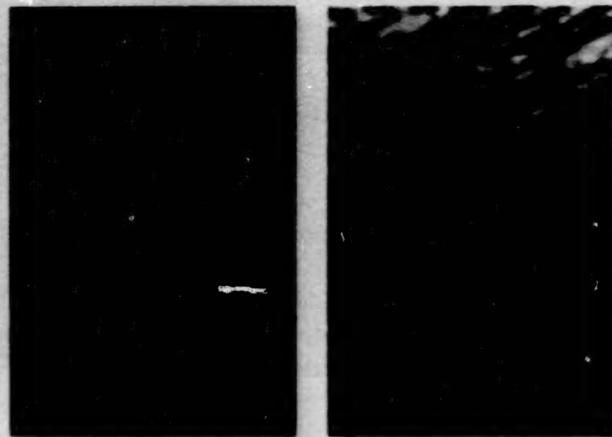
On the MEA-A1 mission, germanium selenide crystals were formed inside heated quartz ampoules. The size of the crystal and the location of crystal formation were far different than expected. On Earth, the crystals were small and formed a crust around the ampoule walls. In space, larger crystals nucleated in the middle of the ampoule away from the walls. The crystals were almost flawless, with strikingly improved surface qualities. The experiment was repeated on the MEA-A2 mission (flown with Spacelab D1), and similar results were obtained. This indicates that the vapor-transport technique may be an excellent way to produce crystals in space.



Silicon crystals grown in the Mirror Heating Facility (Spacelab 1) had striations similar to crystals grown on Earth. This led scientists to the conclusion that flows driven by surface tension, present in both 1-g and 0-g, rather than gravitational convection, caused the striations.



A payload specialist inserts a sample into the Gradient Heating Facility.



This eutectic of silver and copper processed in space (left) has a finer structure than the sample processed in the same facility on the ground (right).

Metals, Alloys, and Composites: Scientists continue in their quest to improve metallurgical processes, to form better and novel alloys, and to test theories of metal and alloy processing. This type of processing is so complex that it is difficult to measure and model and even more difficult to control. In space, gravity-related phenomena such as convection are reduced, thus eliminating one complex mechanism for mass and heat transfer and simplifying processes for study.

Perhaps the most fundamental advances made in this area on the Shuttle were in understanding how liquified metals diffuse through each other. Diffusion is the movement of atoms past each other; each material has an inherent diffusion coefficient which describes the ability of atoms to move past each other in that material. Gravity-induced convection complicates diffusion measurements on Earth. Spacelab 1 results indicate that space may be the only place where accurate measurements of the coefficients can be made.

Spacelab 1 experiments showed that pure diffusion can be measured so well in space that thermomigration, also called Soret diffusion, is clearly evident. In a binary mixture in which a temperature gradient is maintained, thermomigration causes the constituents to separate according to their atomic weights. The heavier components will migrate toward the cool end of a furnace and the light components will migrate toward the hot end.

For one Spacelab experiment studying thermomigration, the Gradient Heating Facility, which had hot and cold ends to force a physical process to move in a given direction, provided a temperature drop of 648 degrees Fahrenheit from one end of the sample to the other. A sample of tin containing 0.5 percent cobalt was processed. Due to convective mixing, samples processed on the ground were evenly mixed; however, those processed in flight had double the cobalt concentration at the hot end of the ampoule. The accuracy of these measurements was 300 times better than ground-based experiments had achieved. This experiment may influence research to separate isotopes of metals with greater efficiency.

A similar experiment using common isotopes of tin measured its diffusion coefficient with an accuracy 10 to 40 times greater than the best ground-based experiments. Radiation analysis showed how much of the trace quantity of tin-124 had migrated into the tin-112 making up the bulk of the sample. Because isotopes are chemically identical, any movement of one into the other must be caused purely by diffusion instead of any chemical effect. Several tubes with different diameters were used to isolate variations caused by the walls. A striking

result was the high accuracy, unmatched in ground tests, of data indicating that the diffusion coefficient was much smaller than indicated by ground-based experiments. Accuracy in this figure will greatly improve the ability to model metal-mixing experiments both on the ground and in space, and the improved precision of diffusion measurements at different temperatures will help scientists establish the mechanism by which diffusion takes place in liquid metals.

A large number of alloys belong to an interesting class called eutectics. A eutectic material is a mixture of two materials that has a lower melting point than either material alone. In the liquid phase the two materials that form a eutectic are completely miscible, but in the solid phase they are almost completely immiscible. Therefore, as two materials that form a eutectic solidify, they go from a single liquid phase to two distinct solid phases. Because many alloys are eutectics, scientists are interested in understanding the distribution of the immiscible solid phases. If a eutectic alloy is directionally solidified, long rods or lamella (sheets of one phase sandwiched between another phase) are formed; the alloy may have desirable properties, such as added strength or higher magnetic performance in one direction.

As a result of space experiments, scientists are reexamining a classical theory on the formation of eutectics. The theory assumes there is no convection in the melt when the eutectic materials are processed in space. The theory works quite well on Earth, but an earlier rocket experiment produced a eutectic with rod spacing quite different than what was predicted by the classical theory. This was puzzling, but when the experiment was repeated in ground laboratories where a magnetic field was used to damp convection, experimenters got the same results. Scientists were faced with a paradox: a theory based on no convection worked fine when convection was present, but the theory did not work when convection was absent.

For the Spacelab 1 mission, the same experiment was repeated with other eutectic systems. Some of them had smaller rod spacing than predicted, others had the predicted rod spacing, and others even had larger rod spacing than predicted by the theory. Apparently, space experiments have revealed some unidentified effect that controls rod spacing in eutectic systems. More space samples will have to be processed to determine if the classical theory on convection in eutectic processing needs revision.

Glasses and Ceramics: Optical engineering is being revolutionized by new glasses, crystals, and other materials that surpass conventional substances in quality. However, production of these superior materials is difficult, because some glasses have chemical mixes that are highly reactive with containers while others are extremely sensitive to contamination levels of even a few parts per billion. For example, certain fluoride glasses are of great interest for their infrared transmission properties. These glasses can be made on Earth, but trace contaminants from processing containers have prevented them from reaching their theoretical performance level.

Containerless processing, in which a sample is suspended and manipulated without touching contaminating containers, is an attractive solution to these problems. Containerless processing on massive samples can only be done in microgravity where the acoustic and electromagnetic forces used for suspension and manipulation are not overwhelmed by gravity. Currently, there is only a limited amount of data on how materials might be processed in this manner, but experiments such as the Spacelab 3 Drop Dynamics Module (DDM), which demonstrated that liquid drops could be levitated and manipulated acoustically in microgravity, will help scientists develop instruments and techniques for containerless processing of glasses and other materials. (The DDM results are discussed in the Fluid and Chemical Processes section of this chapter.)

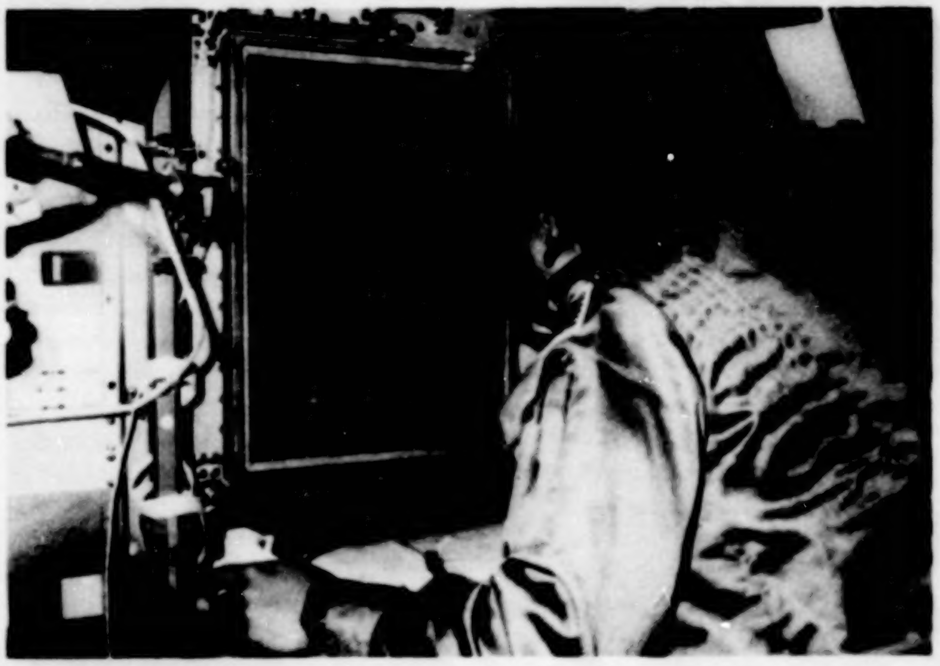
For the first time, a glass sample was levitated, melted, and resolidified in space in the Single Axis Acoustic Levitator experiment carried aboard MEA-A2. This sample, a spherical glass shell containing an air bubble, was similar to fuel containers for inertially confined fusion experiments. These fusion experiments require that the glass shell have extremely smooth inner and outer surfaces and that the wall of the shell be perfectly uniform in thickness. The perfection in surface smoothness, wall thickness, sphericity, and concentricity required for large diameter glass shells that are inertially confined fusion targets is essentially impossible to maintain on Earth due to gravity-induced distortion; however, it might be possible to obtain this perfection by reprocessing the glass shell using containerless processing techniques in microgravity. When this experiment was conducted in space,

the sample melted and remained suspended. However, just before it resolidified, the air bubble inside migrated to the surface and broke through the outer wall, leaving a solid glass sphere. Bubble migration in the absence of gravitational convection is of great interest to materials scientists, and they are analyzing this experiment to determine why the bubble reacted in this unexpected fashion.

Two other samples were levitated and melted during the MEA-A1 and MEA-A2 missions, but when the samples were cooled, the levitation became unstable and the samples became attached to the sample confinement cage. More experiments are needed to study containerless processing of glass and other types of samples.

Fluid and Chemical Processes:
In microgravity, it is possible to observe fluid movement and behavior that are masked by gravity-driven flows on Earth. Fluid physics research may give scientists insight into crystal growth, glass processing, and other material processes.

The goal of the Spacelab 1 Fluid Physics Module experiment was to investigate fluid processes in microgravity. Two-inch-wide disks were used to support a column of liquid with free cylindrical surfaces. Because gravity does not collapse the liquid column in space, the disks were pulled apart to create a bridge almost 3 inches long (8 centimeters). (On Earth, 1/8th inch or 0.3 centimeters is the greatest possible height for columns of this fluid.) The disks were rotated together and in opposite directions and heated unevenly so that the behavior of the fluid under forces other than gravity could be observed.



The Drop Dynamics Module provided the first opportunity to answer 300-year old questions about the behavior of drops. Drops such as this one were acoustically suspended and manipulated.

One experiment used a fluid column to study Marangoni convection, which occurs when temperature gradients change the surface tension of a molten material, making the liquid surface move. By suspending tracers in the liquid bridge, scientists were able to observe fluid flows attributed to Marangoni convection in a fluid column that was almost 25 times bigger than any ever studied on Earth. Although detailed studies of Marangoni convection have been done on a small scale in terrestrial laboratories, it had never been studied in such a large sample. Scientists are analyzing films of this large fluid column to study detailed processes that occurred without the gravitational distortions that complicate measurements on Earth.

The Spacelab 3 Drop Dynamics Module provided the first opportunity to answer scientific questions that had been asked for more than 300 years. These fluid physics theories could not be studied experimentally because gravity precludes levitation of liquids without introducing forces that significantly mask the phenomena being studied. In microgravity, sound waves were used to levitate and manipulate drops of water and glycerin. As the principal investigator controlled the experiment, the drops were photographed.

The experiments confirmed that some of the age-old assumptions about drop behavior in relatively simple situations were correct. Other results were unexpected. The bifurcation point when a spinning drop takes a dog-bone shape in order to hold itself together came earlier than predicted under certain circumstances. In another case, a rotating dog-bone drop returned to a spherical shape and stopped rotating

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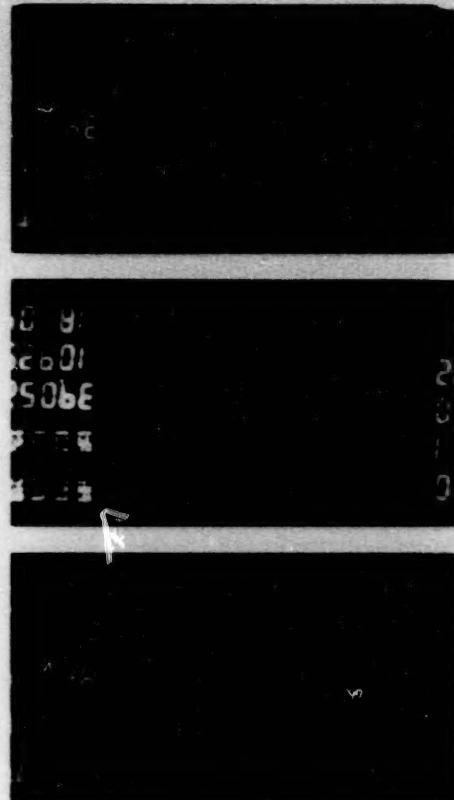
Via video links between Spacelab and the ground, scientists on the ground were able to watch drop experiments.



These images made in space show patterns of fluid convection cells and wavy disturbances as observed in the Geophysical Fluid Flow Cell (GFFC). This experiment modeled basic fluid flows as well as those that might be found in planetary and stellar atmospheres. Gravity distorts similar studies made in ground-based laboratories.

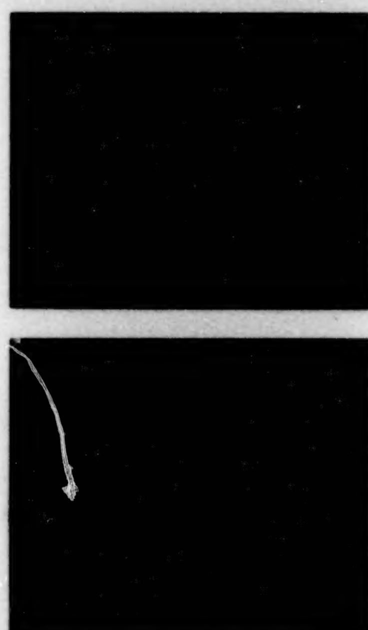
quickly rather than slowly, apparently from differential rotation on the inside. By analyzing the physical processes inside drops suspended in microgravity, scientists have the opportunity to experimentally test basic fluid physics theories that have applications in other areas of physics.

The drop experiments also demonstrated a potentially valuable processing technique. By suspending glasses and other materials inside a processing chamber so that the material does not touch container walls, scientists may be able to process purer specimens than those produced on Earth. The value of having an expert scientist to conduct space experiments was evident as well. The principal investigator was a part of the crew, enabling him to repair the instrument when it developed a problem on orbit, make valuable real-time observations, and adjust the experiment parameters to view subtle changes in drop behavior.

For another Spacelab 3 experiment, the Geophysical Fluid Flow Cell, a rotating spherical system was used to model patterns of convection and other interesting fluid motions that are found in stellar and planetary atmospheres. Fluid physicists are interested in the flow characteristics of the fluids themselves, and meteorologists, planetologists, and astrophysicists are interested in the large-scale circulation of fluids under the influence of rotation, gravity, and heating.

The thermally driven motion of a fluid in a spherical experiment is similar to that in a thermally driven rotating, shallow atmosphere or in a deep ocean on a spherical planet. It is very difficult to do controlled experiments with this type of system in an Earth-based laboratory, because terrestrial gravity distorts the flow patterns in ways that do not correspond to actual planetary flows. In space, gravity is reduced and electrostatic forces can be used to mimic gravity on a scale appropriate for the model. A 16-mm movie camera photographed global flow patterns as revealed by dyes and schlieren patterns resulting from fluid density changes.

More than 50,000 images were recorded in 103 hours of simulations. Some expected features such as longitudinal banana-shaped cells like those which may exist on the sun were observed. Other images are being compared to current models of atmos-

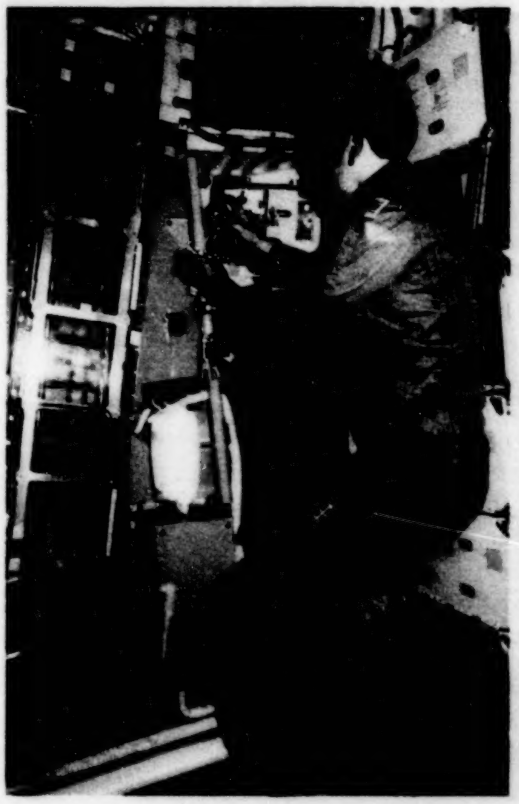


Computer plots of fluid flows were made from the GFFC images. The yellow reveals upward flow and the blue represents downward flow.

pheric flow patterns for planets such as Jupiter and Uranus. Space is the only place where these models can be tested accurately.

A Spacelab 2 experiment investigated the basic properties and behavior of a material that is not yet well understood but may be useful for new technology. Liquid helium is of interest as a coolant for infrared telescopes and detectors that operate at extremely low temperatures. Below 2.2 degrees Kelvin (-456 degrees Fahrenheit), liquid helium is transformed into superfluid helium, which moves freely through pores so small that they block normal liquid and conducts heat about 1,000 times better than copper. Because superfluid helium is an entirely different state of matter from conventional fluids, it is being studied in space to improve our fundamental understanding of the physics of matter. Many subtleties of superfluid helium behavior are unknown because gravitational effects disturb the superfluid state, where the laws of quantum mechanics predominate over the laws of everyday existence.

Future space experiments are planned for which the temperature of the helium must be constant to a few millionths of a degree. Spacelab 2 experiments showed that the helium temperature does remain constant and stable. The large-scale motions of liquid helium also are important because they could disturb the attitude control systems essential for pointing telescopes of large helium-cooled observatories planned for the 1990s. A Spacelab 2 bulk fluid motion experiment measured the amplitude and decay of the sloshing motion caused by small orbiter motions. It appears the motions are so small that they will not affect the ultrasensitive telescopes and experiments.



The Continuous Flow Electrophoresis System is used to separate and purify biological cells and proteins.

Biological Processing: Biological materials such as cells, proteins, and enzymes can be processed to create valuable medical and pharmaceutical products. Before many of these materials can be used for medical purposes, they must be separated from other substances. Convection and sedimentation on Earth make it difficult to separate these biological substances in ultra-pure forms and high concentrations.

The Continuous Flow Electrophoresis System (CFES) is used to separate and purify biological cells and proteins in space. This instrument has been flown six times, and after each flight the instrument and technique have been refined for more effective processing. Investigators have been able to increase the concentration of material separated and purified during a given period. For two proteins, the throughput of desired product was 500 times greater than achieved on the ground in the same instrument. The space-produced substances are being evaluated by a pharmaceutical company.

Materials and life scientists also share an interest in protein crystals. Single crystals of sufficient size and perfection are needed to analyze the molecular structure of numerous proteins and enzymes. Knowledge of the structure is a prerequisite for optimal utilization of the proteins for medical, pharmaceutical, and bioengineering applications.

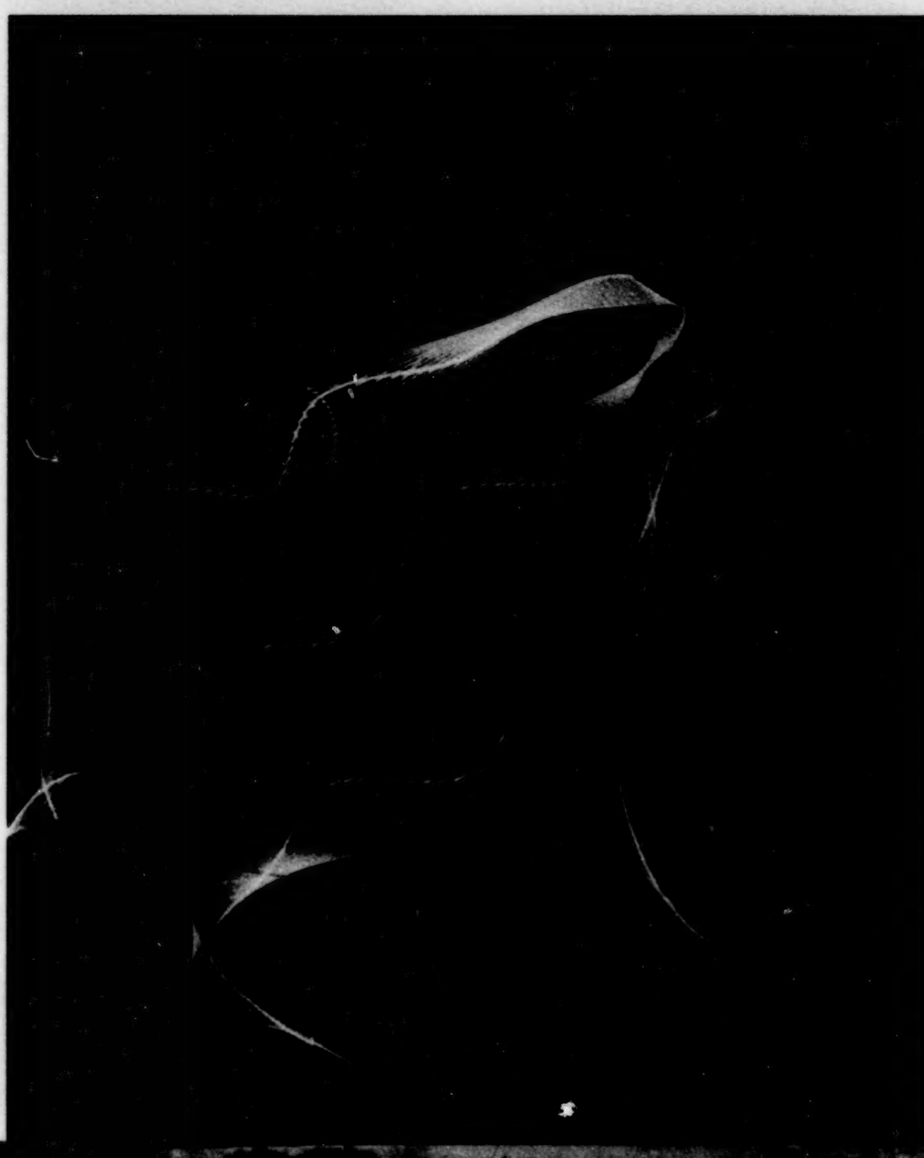
These crystals can be grown by the simultaneous counter-diffusion of a protein and salt solution into a buffer solution. As the proteins start to crystallize on Earth, the different densities of the crystal and the solution result in convection, which can lead to a large number of small, imperfect crystals. Thus, one of the great limitations in protein crystal research has been the inability to produce large, pure crystals for analysis.

Fortunately, preliminary experiments aboard the Shuttle and Spacelab indicate that much larger and higher quality crystals can perhaps be grown in space where convection is reduced and crystals float freely in solution. During the Spacelab 1 mission, crystals of lysozyme (a basic protein) and beta-galactosidase (a key genetic ingredient) were produced of sufficient size and perfection for X-ray structural analysis. The crystals were several times larger than those produced in the same facility on the ground.

The successful Spacelab 1 experiment sparked a united effort by a team of scientists who developed an apparatus that uses vapor diffusion to grow protein crystals. Several proteins have been processed in this developmental apparatus; many of the space crystals were large, and indications are that the quality is high. The crystals also formed more distinctly, rather than clumping together. In the case of one protein, a new crystal form was identified and has since been produced in ground laboratories. Based on these preliminary results, a larger facility with a more controlled environment is being developed.

These lysozyme crystals processed during Spacelab 1 were several times larger than those produced in the same facility on the ground.

It is possible to define the structure of single protein crystals using X-ray crystallography, but the ability to do this depends on the size and perfection of the crystal. These space-processed canavalin crystals indicate the potential of growing high quality protein crystals in space.



Computer-generated model of a protein structure

Gaining Experience to Shape the Future: These first-generation space experiments have proven the feasibility of a variety of materials processing techniques in space. These experiments have provided some valuable fundamental knowledge, revealing the nature of phenomena that are masked or not easily observed on Earth. A second generation of experiments with more clearly defined objectives and better instrumentation is needed to quantify results.

Spacelab has proven that crewmembers acting as operators and observers will be extremely important for experimentation, because unanticipated results can only be spotted by the trained eye, and a simple adjustment may rescue or change the nature of an experiment. On the Space Station, with crewmembers to observe experiments and equipment for analyzing samples in orbit, it will not be necessary to return all specimens to Earth for characterization before running the next experiment in space. Productivity will be enhanced by the additional power and space for experiments on the Space Station. The Space Station will use sophisticated data systems to display real-time data to investigators in space and on the ground. This will make collaboration between scientists more practical. Data will be archived so that each experiment can build on results from previous studies.

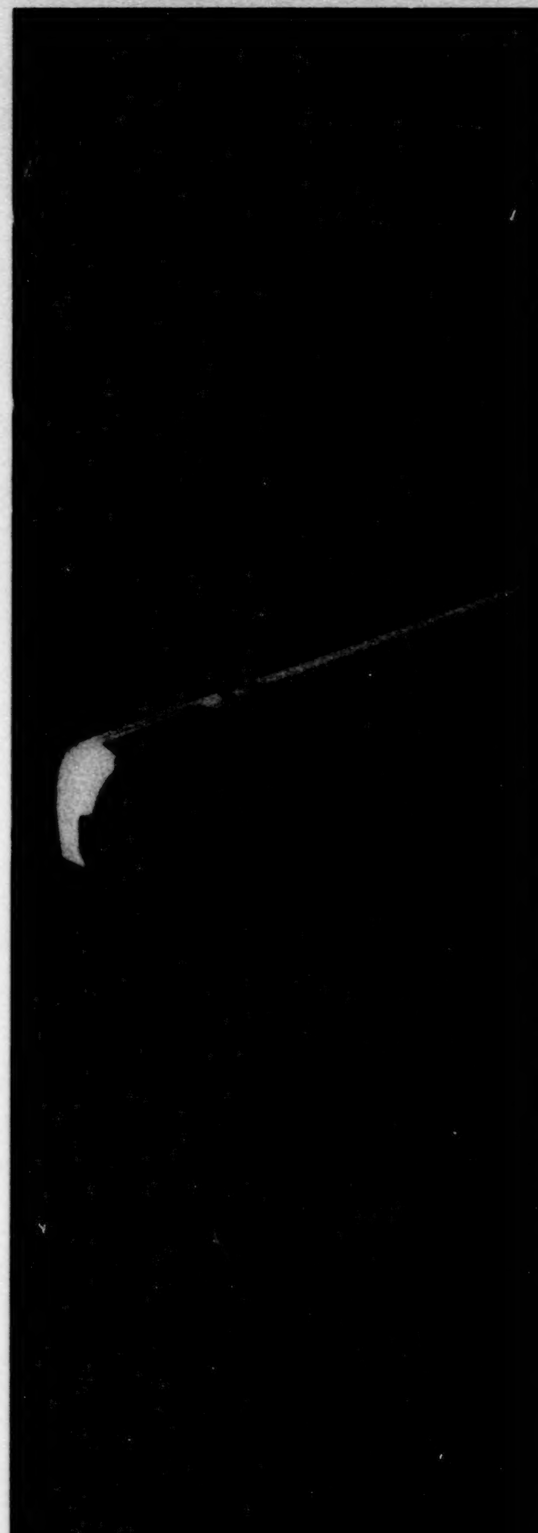
The Space Station will permit long-duration experiments in an environment more similar to terrestrial laboratories. A dramatic increase in experiment time over the few tens of hours performed to date will occur. Experiments in microgravity will stretch over periods comparable to those on Earth, greatly increasing the types of materials that can be processed to full term. This will be a great advantage to experiments in areas such as solution and vapor crystal growth which require 15 to 30 days of continuous growth to produce crystals of the desired size.

It may be that experiments that do not need a pressurized module or frequent human intervention can be attached outside on the station or flown on free flyers. Free flyers will have a more stable microgravity environment that is not disturbed by crew motions and other Space Station activities. They will be ideal for mature manufacturing facilities where processing is routine and products only need retrieval. Teleoperated or remote vehicles may be used to retrieve and replace samples.

The Shuttle/Spacelab has helped train both investigators and crewmembers for future materials processing experiments. Scientist crewmembers and investigators on the ground have learned to work together, observing and adjusting parameters to improve experiment results.

The upcoming International Microgravity Laboratory (IML) missions will give scientists around the world an opportunity to coordinate research. Some experiments from previous missions, such as the Spacelab 3 crystal growth experiments, will be reflown and some new experiments will be attempted. This mission will provide valuable research opportunities to U.S. scientists and to their international partners who will work with them aboard the Space Station. Aboard the Spacelab J mission, the Japanese will do their first manned materials processing experiments in space.

NASA continues to examine ways to improve Shuttle/Spacelab research. In the future it may be possible to extend missions, providing longer periods for research. This will allow a larger experiment base to be developed and contribute to the evolution of more mature hardware to take advantage of long-term stays aboard the Space Station. ■



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Studying Materials and Processes in Microgravity

Materials Science Investigations

OSS-1/STS-3

- *Monodisperse Latex Reactor System***
  J.W. Vanderhoff, Lehigh University
  Bethlehem, Pennsylvania

STS-6

- *Continuous Flow Electrophoresis System****
  D. Clifford, McDonnell Douglas Aerospace Co.
  St. Louis, Missouri

Materials Experiment Assembly – A1 (MEA-A1)/STS-7

Gradient General Purpose Rocket Furnace

- *Vapor Growth of Alloy-Type Semiconductor Crystals*
  H. Wiedemeier, Rensselaer Polytechnic Institute
  Troy, New York

Isothermal General Purpose Rocket Furnace

- *Liquid Phase Miscibility Gap Materials*
  S.H. Gelles, S.H. Gelles Laboratories, Inc.
  Columbus, Ohio

Single Axis Acoustic Levitator

- *Containerless Processing of Glass Melts*
  D.E. Day, University of Missouri
  Rolla, Missouri

Materialwissenschaftliche Autonome Experimente Unter Schwerelosigkeit (MAUS)/STS-7

- *Solidification Front*
  H. Klein, DFVLR
  Cologne, Germany
- *Stability of Metallic Dispersions*
  G.H. Otto, DFVLR
  Cologne, Germany

Spacelab 1/STS-9

Materials Science Double Rack —

Fluid Physics Module

- *Capillary Forces in a Low-Gravity Environment*
  J.F. Padday, Kodak Research Laboratory
  Harrow, England
- *Coupled Motion of Liquid-Solid Systems in Near-Zero Gravity*
  J.P.B. Vreeburg, National Aerospace Laboratory
  Amsterdam, The Netherlands
- *Floating Zone Stability in Zero-Gravity*
  I. Da Riva, University of Madrid, Spain
- *Free Convection in Low Gravity*
  L.G. Napolitano, University of Naples, Italy
- *Interfacial Instability and Capillary Hysteresis*
  J.M. Haynes, University of Bristol, United Kingdom
- *Kinetics of the Spreading of Liquids in Solids*
  J.M. Haynes, University of Bristol, United Kingdom
- *Oscillation of Semi-Free Liquid Spheres in Space*
  H. Rodot, National Center for Scientific Research
  Paris, France

Gradient Heating Facility

- *Lead-Telluride Crystal Growth*
  H. Rodot, National Center for Scientific Research
  Paris, France
- *Solidification of Aluminum-Zinc Vapor Emulsion*
  C. Potard, Center for Nuclear Studies
  Grenoble, France
- *Solidification of Eutectic Alloys*
  J.J. Favier and J.P. Praizey
  Center for Nuclear Studies
  Grenoble, France
- *Thermodiffusion in Tin Alloys*
  Y. Malméjac and J.P. Praizey
  Center for Nuclear Studies
  Grenoble, France
- *Unidirectional Solidification of Eutectics*
  G. Müller, University of Erlangen, Germany

Isothermal Heating Facility

- *Bubble-Reinforced Materials*
  P. Gondi, University of Bologna, Italy
- *Dendrite Growth and Microsegregation of Binary Alloys*
  H. Fredriksson, The Royal Institute of Technology
  Stockholm, Sweden
- *Emulsions and Dispersion Alloys*
  H. Ahlborn, University of Hamburg, Germany
- *Interaction Between an Advancing Solidification Front and Suspended Particles*
  D. Neuschütz and J. Pötschke
  Krupp Research Center
  Essen, Germany
- *Melting and Solidification of Metallic Composites*
  A. Deruyttere, University of Leuven, Belgium
- *Metallic Emulsion Aluminum-Lead*
  P.D. Caton, Fulmer Research Institute
  Stoke Poges, United Kingdom
- *Nucleation of Eutectic Alloys*
  Y. Malméjac, Center for Nuclear Studies
  Grenoble, France
- *Reaction Kinetics in Glass*
  G.H. Frischat, Technical University of Clausthal, Germany
- *Skin Technology*
  H. Sprenger, MAN Advanced Technology
  Munich, Germany

- Solidification of Immiscible Alloys
  H. Ahlborn, University of Hamburg, Germany
- Solidification of Near-Monotectic Zinc-Lead Alloys
  H.F. Fischmeister, Max Planck Institute
  Stuttgart, Germany
- Unidirectional Solidification of Cast Iron
  T. Luyendijk, Delft University of Technology
  The Netherlands
- Vacuum Brazing
  W. Schönherr and E. Siegfried
  Federal Institution for Material Testing
  Berlin, Germany
- Vacuum Brazing
  R. Stickler and K. Frieler
  University of Vienna, Austria

Mirror Heating Facility

- Crystallization of a Silicon Drop
  H. Kölker, Wacker-Chemie
  Munich, Germany
- Floating Zone Growth of Silicon
  R. Nitsche and E. Eyer
  University of Freiburg, Germany
- Growth of Cadmium Telluride by the Traveling Heater Method
  R. Nitsche, R. Dian, and R. Schönholz
  University of Freiburg, Germany
- Growth of Semiconductor Crystals by the Traveling Heater Method
  K.W. Benz, Stuttgart University, and
  G. Müller, University of Erlangen, Germany

Special Equipment

- Adhesion of Metals in UHV Chamber
  G. Ghersini
  Information Center of Experimental Studies, Italy
- Crystal Growth by Co-Precipitation in Liquid Phase
  A. [illegible], F. Le Faucheux, and M.C. Robert
  Univ[illegible] of Pierre and Marie Curie, Paris, France
- Crystal Growth of Proteins
  W. Littke, University of Freiberg, Germany
- Mercury Iodide Crystal Growth
  R. Cadoret, Laboratory for Crystallography and Physics
  Les Cezeaux, France
- Organic Crystal Growth
  K.F. Nielsen, G. Galster, and I. Johannson
  Technical University of Denmark
  Lyngbyg, Denmark
- Selfdiffusion and Interdiffusion in Liquid Metals
  K. Kraatz, Technical University of Berlin, Germany

Spacelab 3/51-B

Crystal Growth Facility

- Mercury Iodide Crystal Growth*
  R. Cadoret and P. Brisson
  Laboratory for Crystallography and Physics
  Les Cezeaux, France

Drop Dynamics Module

- Dynamics of Rotating and Oscillating Free Drops
  T. Wang, NASA Jet Propulsion Laboratory
  Pasadena, California

Fluid Experiment System

- Solution Growth of Crystals in Zero Gravity System
  R. Lal, Alabama A&M University
  Huntsville, Alabama

Geophysical Fluid Flow Cell

- Geophysical Fluid Flow Cell Experiment
  J.E. Hart, University of Colorado
  Boulder, Colorado

Vapor Crystal Growth System

- Mercuric Iodide Growth
  W.F. Schnepple, EG&G, Inc., Goleta, California

Spacelab 2/51-F

- Properties of Superfluid Helium in Zero-Gravity
  P.V. Mason, NASA Jet Propulsion Laboratory
  Pasadena, California
- Protein Crystal Growth****
  C.E. Bugg, University of Alabama in Birmingham, Alabama

Spacelab D1/61-A

Materials Science Double Rack —

Cryostat

- Protein Crystals*
  W. Littke, University of Freiburg, Germany

Fluid Physics Module

- Capillary Experiments*
  J.F. Padday, Kodak Research Laboratory
  Harrow, United Kingdom
- Convection in Nonisothermal Binary Mixtures
  J.C. Legros, University of Brussels, Belgium
- Floating-Zone Hydrodynamics*
  I. Da Riva, University of Madrid, Spain
- Forced Liquid Motions*
  J.P.B. Vreeburg, National Aerospace Laboratory
  Amsterdam, The Netherlands

Materials Science Investigations (continued)

Materials Science Double Rack (continued)—

- *Marangoni Convection*
  A.A.H. Drinkenburg, University of Groningen
  The Netherlands
- *Marangoni Flows**
  L.G. Napolitano, University of Naples, Italy
- *Separation of Fluid Phases*
  R. Naehle, DFVLR
  Cologne, Germany

Gradient Heating Facility

- *Cellular Morphology in Lead-Thallium Alloy*
  B. Billia, University of Marseille, France
- *Dendritic Solidification of Aluminum-Copper Alloys*
  D. Camel, Center for Nuclear Studies
  Grenoble, France
- *Doped Indium Antimonide and Gallium Indium Antimonide*
  C. Potard, Center for Nuclear Studies
  Grenoble, France
- *Ge-GeI$_4$ Chemical Growth*
  J.C. Launay, University of Bordeaux, France
- *Ge-I$_2$ Vapor Phase*
  J.C. Launay, University of Bordeaux, France
- *Thermal Diffusion*
  J. Dupuy, University of Lyon, France
- *Thermomigration of Cobalt in Tin*
  J.P. Praizey, Center for Nuclear Studies
  Grenoble, France

High Temperature Thermostat

- *Self- and Interdiffusion**
  K. Kraatz, Technical University of Berlin, Germany

Isothermal Heating Facility

- *Homogeneity of Glasses**
  G.H. Frischat, Technical University of Clausthal, Germany
- *Liquid Skin Casting of Cast Iron**
  H. Sprenger, MAN Advanced Technology
  Munich, Germany, and
  I.H. Nieswagg, Delft University of Technology
  The Netherlands
- *Nucleation of Eutectic Alloys**
  Y. Malméjac, Center for Nuclear Studies
  Grenoble, France
- *Ostwald Ripening**
  H.F. Fischmeister, Max Planck Institute
  Stuttgart, Germany
- *Particle Behavior at Solidification Fronts*
  D. Langbein, Battelle-Institute
  Frankfurt, Germany
- *Separation of Immiscible Alloys**
  H. Ahlborn, University of Hamburg, Germany
- *Skin Technology**
  H. Sprenger, MAN Advanced Technology
  Munich, Germany, and
  I.H. Nieswaag, Delft University of Technology
  The Netherlands
- *Solidification of Composite Materials**
  A. Deruyttere, University of Leuven, Belgium
- *Solidification of Suspensions**
  J. Pötschke, Krupp Research Center
  Essen, Germany

Mirror Heating Facility

- *Floating Zone Growth of Silicon**
  R. Nitsche, University of Freiburg, Germany
- *Growth of Cadmium Telluride by the Traveling Heater Method**
  R. Nitsche, University of Freiburg, Germany
- *Growth of Semiconductor Crystals by the Traveling Heater Method**
  K.W. Benz, University of Stuttgart, Germany
- *Melting of Silicon Sphere**
  H. Kölker, Wacker-Chemie
  Munich, Germany

Materials Science Experiment Double Rack for Experiment Modules and Apparatus —

Gradient Furnace with Quenching Device

- *Aluminum/Copper Phase Boundary Diffusion*
  H.M. Tensi, Technical University, Munich, Germany
- *Solidification Dynamics*
  S. Rex and P.R. Sahm, RWTH
  Aachen, Germany

High-Precision Thermostat

- *Heat Capacity Near Critical Point*
  J. Straub, Technical University Munich, Germany

Monoellipsoid Heating Facility

- *Indium Antimonide-Nickel Antimonide Eutectics*
  G. Müller, University of Erlangen, Germany
- *Traveling Heater Method (PbSnTe)*
  M. Harr, Battelle-Institute, Frankfurt, Germany
- *Vapor Growth of Cadmium Telluride*
  R. Nitsche, University of Freiburg, Germany

Process Chamber —

Holographic Interferometric Apparatus

- *Bubble Transport*
  A. Bewersdorff, DFVLR
  Cologne, Germany
- *GETS*
  A. Ecker and P.R. Sahm, RWTH
  Aachen, Germany
- *Phase Separation Near Critical Point*
  H. Klein, DFVLR
  Cologne, Germany
- *Surface-Tension Studies*
  D. Neuhaus, DFVLR
  Cologne, Germany

Interdiffusion Salt Melt Apparatus

- *Interdiffusion*
  J. Richter, RWTH
  Aachen, Germany

Marangoni Convection Boat Apparatus

- *Marangoni Convection*
  D. Schwabe, University of Giessen, Germany

Materials Experiment Assembly-A2 (MEA-A2)/61-A *****

Gradient General Purpose Rocket Furnace

- *Semiconductor Materials*
  R.K. Crouch, NASA Langley Research Center
  Hampton, Virginia
- *Vapor Growth of Alloy-Type Semiconductor Crystals**
  H. Wiedemeier, Rensselaer Polytechnic Institute
  Troy, New York

Isothermal General Purpose Rocket Furnace

- *Diffusion of Liquid Zinc and Lead*
  R.B. Pond, Marvalaud, Inc.
  Westminster, Maryland
- *Liquid Phase Miscibility Gap Materials*
  S.H. Gelles, S.H. Gelles Laboratories, Inc.
  Columbus, Ohio

Single Axis Acoustic Levitator

- *Containerless Melting of Glass**
  D.E. Day, University of Missouri
  Rolla, Missouri

Materials Science Laboratory-2 (MSL-2)/61-C *****

Automated Directional Solidification Furnace

- *Orbital Processing of Aligned Magnetic Composites*
  D.J. Larson, Grumman Aerospace Corporation
  Bethpage, New York

Electromagnetic Levitation Furnace

- *Undercooled Solidification in Quiescent Levitated Drops*
  M.C. Fleming, Massachusetts Institute of Technology
  Cambridge, Massachusetts

Three-Axis Acoustic Levitator

- *Dynamics of Compound Drops*
  T. Wang, NASA Jet Propulsion Laboratory
  Pasadena, California

Physical Phenomena in Containerless Glass

- *Processing Model Fluids*
  R.S. Subramanian, Clarkson University
  Potsdam, New York

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* Reflight
** 5 flights completed (STS-3, -4, -6, -7, and -11)
*** 6 flights completed (STS-6, -7, -8, 41-D, 51-D, and 61-B)
**** 4 flights completed (Spacelab 2, 51-D, 61-B, and 61-C)
***** MEA-A2 is sometimes referred to as MSL-1;
The MSL-2 mission was the first MSL flight.

Chapter 4

Observing the Sun: Solar Physics

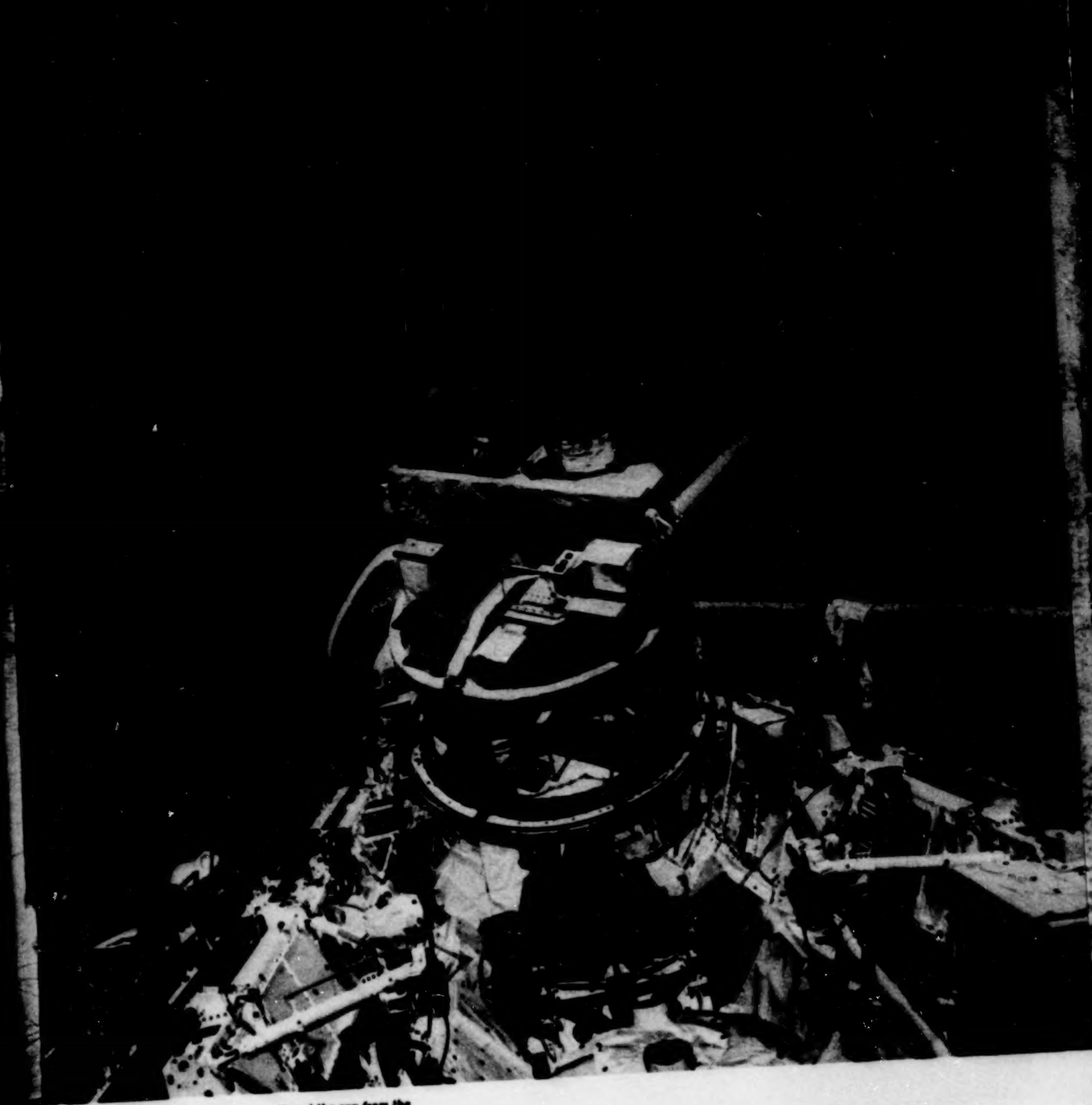
The Shuttle and Spacelab have been used very successfully as an observatory for studying the sun, the nearest and best known star and the source of energy for Earth's environment.

A manned observatory in space has several advantages for viewing the sun. From space, all the sun's radiance, including that normally absorbed by the Earth's atmosphere, can be observed and measured; ultraviolet and X-ray images reveal important features and processes that cannot be viewed through telescopes on the ground. In comparison to a rocket flight that lasts only a few minutes, many more solar images and much larger data sets can be obtained during a week-long Shuttle mission and subsequent reflights. By comparison to an unmanned orbiting observatory, scientists aboard the Shuttle can monitor the sun, select targets for viewing, point and focus and fine tune the instruments, and explore interesting phenomena, exercising the same kind of real-time control that is common in a ground observatory.

The Space Shuttle is an ideal location for a solar observatory for two more reasons. Because it is above the turbulence of the Earth's atmosphere, which seriously degrades the quality of images obtained at ground-based observatories, photos from the Shuttle have far better spatial resolution, enabling us to see much smaller details in the sun's surface. Furthermore, since nighttime on the Shuttle lasts only about 40 minutes, it is much easier to follow the evolution of solar phenomena without long interruptions.

The solar telescopes and detectors flown to date have benefited from the adaptability that is possible on a Shuttle/Spacelab mission. The on-board scientists, the ease of instrument commanding, the availability of real-time data and images to scientists on the ground, and the ability to communicate with the crew and replan observations in response to unexpected events have resulted in very successful use of the Shuttle as a solar observatory.

Solar experiments on Spacelab 2 for the first time used a sophisticated mount for telescopes and detectors; the Instrument Pointing System (IPS), built by the European Space Agency, provided precision pointing and stability independent of spacecraft motion and attitude, making it possible to obtain very high-resolution solar



Spacelab 2 experiments monitored the sun from the Instrument Pointing System, a sophisticated mechanism for aiming telescopes and detectors.

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Crewmembers used controls in a Shuttle workstation to point telescopes at specific areas of the sun.

images and spectral data from this fast-moving observatory.

As the following summaries indicate, Shuttle-based solar investigations are making significant contributions to our understanding of the sun as a star and the effects of solar events on the Earth's environment.

Images of the Sun: Both still photography and video techniques have been used to gain some of the best solar images ever obtained. The telescopes and cameras themselves are designed for high-resolution imaging, and the IPS provides necessary pointing control and stability to achieve clear, detailed images of solar features.

The complement of solar instruments flown on the Spacelab 2 mission functioned collectively as an observatory for detailed examination of the sun. Scientists watched areas as small as 350 kilometers (200 miles) for an entire orbit (as long as an hour) without distortion. From the ground, the limit for unblurred observation is only a few seconds or minutes at a time and then only rarely under ideal observing conditions. Seeing the small, rapidly changing features in sharp focus without distortion on a routine basis from the Shuttle was an exciting, new experience for solar observers.

The extended solar atmosphere (corona), the visible surface (photosphere), and the chromosphere and transition region between the hot corona and the much cooler photosphere came under careful scrutiny. The resultant images reveal very small, very faint structures (solar gases shaped by magnetic fields), slight changes in brightness, small-scale motions, and other details that are improving our knowledge of the sun's behavior. These details provide critical clues to the origin of larger, more turbulent solar changes and thus a better understanding of precursor events, which will result in better predictions of the explosive solar events that affect Earth's atmosphere and the nearby space environment.

Movies of tiny, bubble-like convection cells (granules) also contained surprises. Turbulence in Earth's atmosphere blurs ground observatory images of the sun so much that fine details or subtle changes from one image to the next cannot be seen. From Spacelab, however, scientists could see for the first time that granules in magnetic regions (sunspots, pores, and network boundaries) are quite different than in the quiet, undisturbed sun. The shapes of the very small magnetic pores are irregular, scalloped, and rapidly changing as they attempt to maintain their structure against the encroachment of turbulent surrounding granules.

The movies also provided the first undistorted histories of granule evolution, which will help scientists determine normal and abnormal patterns of development. Cinematography has

During the mission, a solar operations center was set up on the ground, and scientists used the latest data from satellites and ground observatories to pinpoint interesting solar features for closer scrutiny by Spacelab 2 telescopes.

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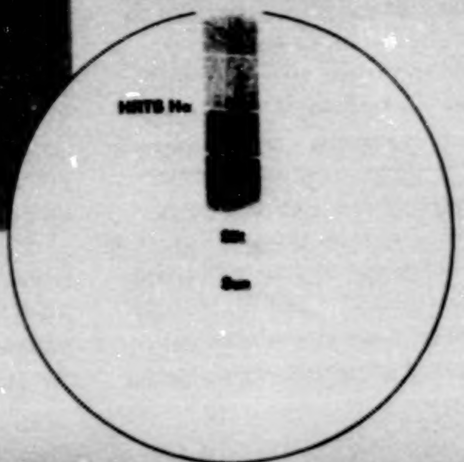
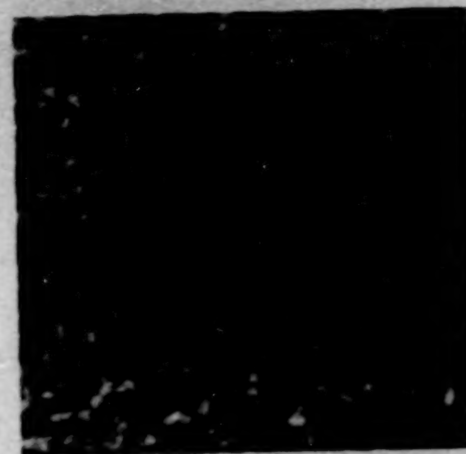
This hydrogen-alpha image from the High Resolution Telescope and Spectrograph (HRTS) shows a sunspot and a wispy filament on the sun. These features are precursors to explosive solar events that affect the Earth's atmosphere and the nearby space environment.





This image from a single frame of the Solar Optical Universal Polarimeter (SOUP) movie shows a sunspot surrounded by granules. For the first time, scientists could see that the activity of granules in magnetic regions such as sunspots differs from those in quiet, undisturbed regions.

The suite of Spacelab 2 solar instruments observed the layers of the sun's surface and atmosphere.

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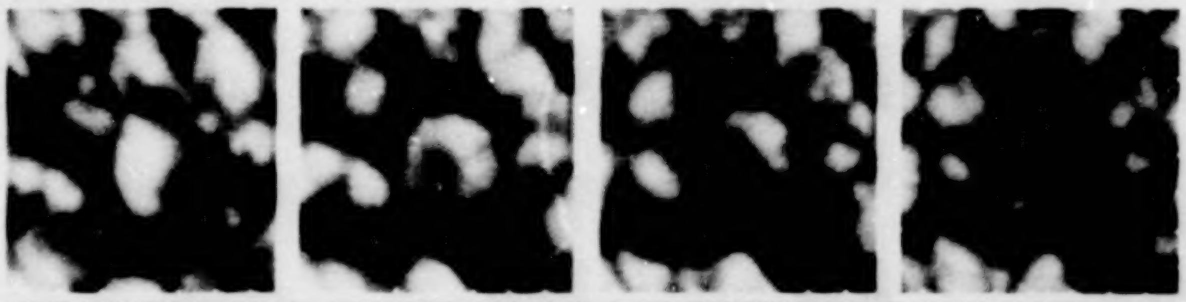
shown that more than half of all granules die a violent death instead of quietly fading away. They either expand until they reach a critical size and explode into many tiny fragments, or they are destroyed by a nearby explosion. The Spacelab 2 movies also disclosed that granules stream radially outward from the center of a sunspot into the surrounding quiet photosphere, a phenomenon never before seen and still unexplained.

Scientists are thrilled with the new images of the sun. The movies are far more consistent in quality from frame to frame than any yet obtained. The Solar Optical Universal Polarimeter (SOUP) instrument, for example, recorded several hours of sunspot and active region observations; the 6,400 frames collected are unique for their extreme image stability. Eight hours of video and 500 still photographs of the sun made by the High Resolution Telescope and Spectrograph (HRTS) instrument in hydrogen-alpha ultraviolet light, plus another 1,300 ultraviolet spectroheliograph exposures, reveal interesting new features of spicules, spiky structures seen along the edge of the sun. While spicules are well recognized from ground-based visible light observations, from the Shuttle scientists observed ultraviolet superspicules that rise twice as high as ordinary spicules. They recorded, for the first time, dramatic changes in the size and shape of the superspicules that may provide the key to understanding these mysterious features.

In addition to these discoveries, postflight film processing and image enhancement techniques are being used to bring to light many features and motions that are completely invisible to ground observers. For example, granules were previously thought to remain roughly in place or have only small random motions during their lifetimes. After sophisticated analysis of the SOUP movies, it has been learned



Solar granules that appear to expand radially at the end of their lifetimes are called exploding granules. An example is shown in this sequence. The bright granule in the center of the first image expands to a puffy state and then explodes, leaving a black circle seen in later images. From ground-based observations, exploding granules were considered rare, but in the SOUP data, it is hard to find areas of quiet sun without them.

The quiet solar limb was recorded by the HRTS ultraviolet spectroheliograph. The image shows the first observation of superspicules, spikes that stand out above the solar limb.

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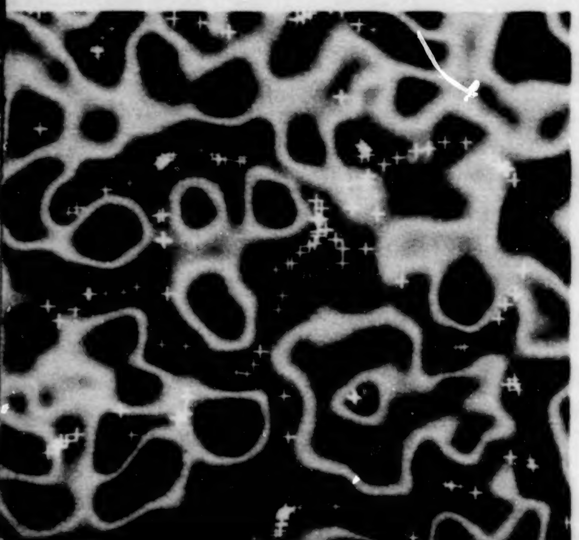
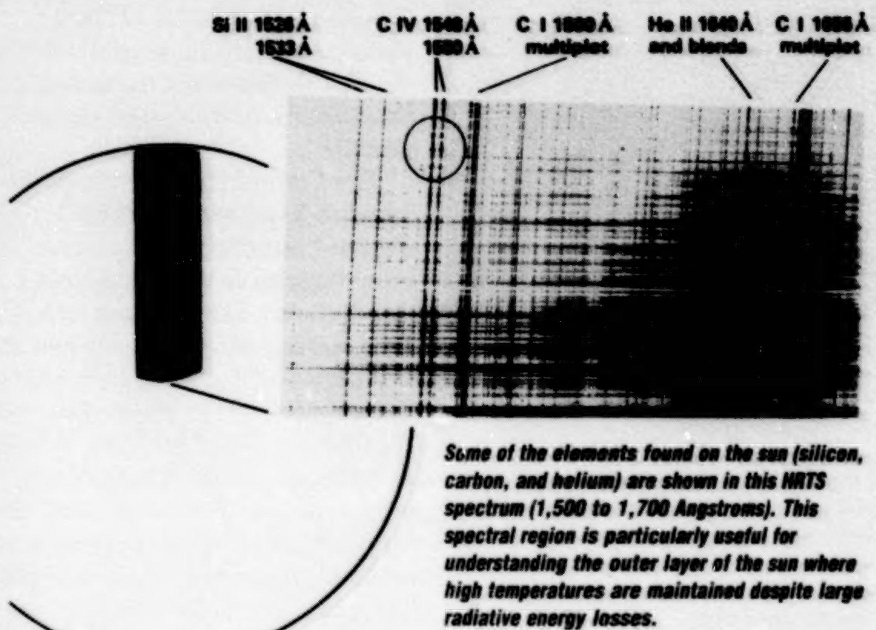
not only that granules are in almost continual motion (with speeds of 3,000 to 4,000 kilometers per hour/ 1,900 to 2,500 miles per hour) but also that they float like corks on top of a much larger flow pattern (called supergranulation and mesogranulation), which consists of giant convective cells 10,000 to 40,000 kilometers (6,000 to 25,000 miles) in diameter. Solar physicists have known about supergranules for over 25 years, but the SOUP observations have provided the first detailed measurements of their flows and their relationships to the large magnetic structures in the sun's atmosphere.

Spectral Data: Spectral analysis – separation of radiation into discrete wavelengths – is another technique used to understand the chemistry and physics of the sun and other stars. Since different chemicals absorb or emit radiation at certain characteristic wavelengths (spectral lines), these "signatures" can reveal much about the composition and motion of solar gases.

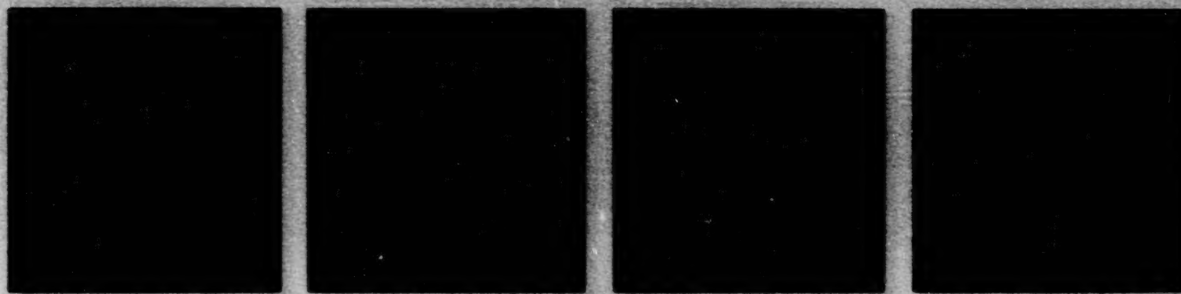
Spectrometers flown on the Spacelab 2 mission recorded a variety of spectra from features on the solar disk and in the corona. The harvest from the HRTS instrument, which can differentiate 2,000 spectral lines in the





Some of the elements found on the sun (silicon, carbon, and helium) are shown in this HRTS spectrum (1,500 to 1,700 Angstroms). This spectral region is particularly useful for understanding the outer layer of the sun where high temperatures are maintained despite large radiative energy losses.

The lower image shows flow patterns (arrows), outflowing material (red), and inflowing material (blue) superimposed on a SOUP sunspot image. Granules may float like corks on these surface flows, as represented by crosses in the upper image. These flow patterns are impossible to calculate from ground-based images.



By measuring the signatures and intensities of various elements, solar physicists can tell more about the sun's physical makeup. These images are part of a catalog made by the Coronal Helium Abundance Spacelab Experiment (CHASE) instrument. Each solar quadrant reveals the spectral intensity of a specific element; the bright areas represent more intense solar activity characteristic of hot, active regions.

Shown in false color are small portions of an ultraviolet emission spectrum obtained by HRTS. The long horizontal streaks marked "EE" are caused by high-speed motions of the solar plasma. Material that moves toward the observer shifts its emission toward higher frequencies (area labeled blue). The emission of material moving away from the observer shifts toward the area labeled red. The velocities of solar material imaged in this spectra are several hundred kilometers per second.

ultraviolet range, was about 19,000 exposures of sunspots, spicules, explosive events, and jets, representing a large new data base for studying the structure and evolution of these features. The HRTS spectral survey of the disk also increased the statistical data base for studying solar features globally.

The Coronal Helium Abundance Spacelab Experiment (CHASE) obtained one of the most accurate measurements of the abundance of solar helium relative to solar hydrogen. By recording ultraviolet emissions from hydrogen and ionized helium, both on the solar disk and in the corona above the limb, an abundance ratio of helium to hydrogen of 10% ±2% was measured. Understanding several important astrophysical processes depends on an accurate accounting of helium in the universe. Since all the helium in the surface layers of the sun is thought to be primitive in origin, data collected on the Spacelab 2 mission are of great importance to cosmologists as well as solar physicists.

From the new spectral information about rapidly changing solar features and the composition of solar gas, scientists are learning more about the physics of energy transfer through the solar atmosphere. Because of the ability to see the ultraviolet sun, high-resolution spectral observations from the Shuttle are especially effective for investigating high-velocity events in the upper solar atmosphere, chromosphere, transition zone, and corona.

The CHASE instrument was able to study the structure and development of active regions in the solar atmosphere. Images in a variety of spectral lines were compiled. These images clearly show that hot active region material forms a bridge between the hot outer layer of the sun (the corona) and the somewhat cooler layer of the sun (the chromosphere) sandwiched between the solar disk and the corona.

Another Spacelab 2 instrument, the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) measured the sun's energy output across the ultraviolet spectrum. The measurements produced a highly accurate spectrum which will be used as a baseline in studying how solar output varies as the sun goes through cycles of minimum and maximum activity. These measurements also are being used by atmospheric physicists.

Solar Models: Both images and spectral data contribute to theoretical modeling of the sun's structure and dynamics. Scientists are attempting to understand how magnetic fields on the sun form and change, how they interact with solar gases, how the various layers of the solar atmosphere differ and interact, and how to predict the occurrence of explosive solar flares.

Data from all the solar investigations mentioned above are affecting solar

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Through careful planning and close coordination between scientists in orbit and on the ground, the Spacelab 2 crew took advantage of solar observing opportunities.

physics theories and models. In addition, the X-ray flare investigation flown on the OSS-1/STS-3 mission was specifically designed to discriminate between competing theories. Despite a contamination problem that complicated data analysis, the experiment gained the most sensitive flare polarization data set ever obtained, placing important experimental constraints on theories of the acceleration and propagation of energetic atomic particles on the sun.

Extending Observations: The dazzling Spacelab 2 images prove that from low-Earth orbit solar instruments do have a clearer view of the sun. These early experiments also show the value of using the eyes and brains of the onboard crew to analyze results and focus instruments on interesting solar events. Without the close interaction between the Spacelab 2 solar physicist crewmembers and scientists on the ground, many observing opportunities would have been lost.

The Spacelab 2 workstation is serving as a model for the controls and monitors that are being designed for the Space Station solar observatory. Like Spacelab, the Space Station will have a solar physicist on board to operate solar instruments and coordinate detailed observing plans with scientists on the ground. Space Station, however, will expand current capabilities by providing additional work areas for repairing and calibrating instruments.

Space Station will provide the continuous, long-duration observations that are obtainable only from a permanent space facility. Several different modes of operation will be possible: around-the-clock, automated observations for a solar cycle or more; scheduled campaigns that are planned months in advance and last from days to months; and unscheduled campaigns that are initiated on short notice in response to solar activity.

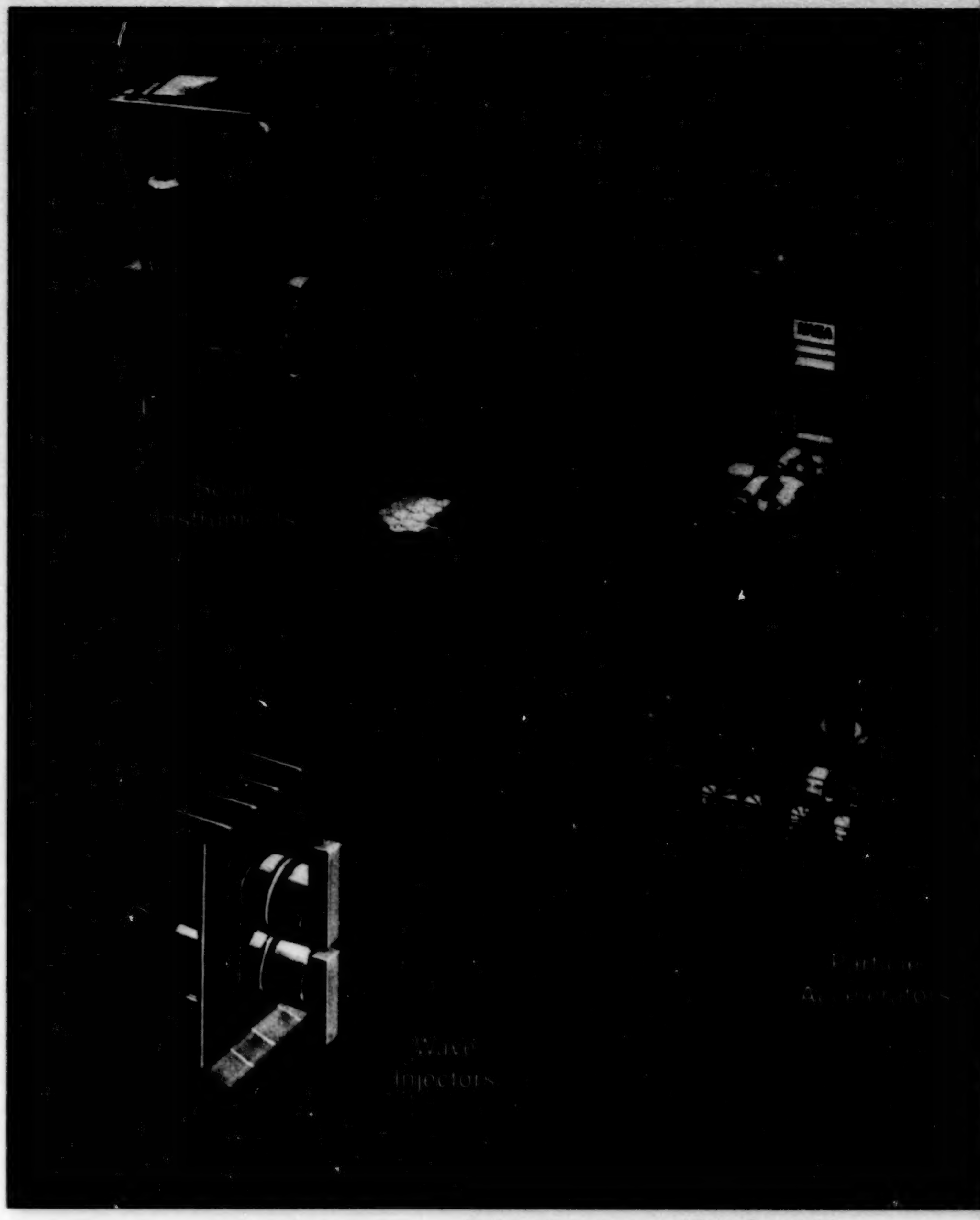
It will be possible to control Space Station instruments from the ground. Instruments will generate up to several hundred million bits of data each second, transmitting some to the Station and some to the ground for real-time analysis. Data will be archived and distributed worldwide. International cooperation will be important since solar activity affects Earth across the globe.

Observing the Sun

Several types of spacecraft and observatories are planned to study diverse solar phenomena. High-resolution telescopes will observe detailed solar features, and low-resolution instruments will study solar variability. A solar observatory may be formed on or near the Space Station. Smaller instruments for studying the acceleration and propagation of high-energy particles, low-frequency radio antennas for studying high-energy electrons accelerated by flares in the solar atmosphere, and other high-resolution telescopes may be included in this observatory to make observations in all wavelengths with full spectral and temporal coverage. This will extend the Spacelab 2 data across the entire electromagnetic spectrum, resulting in the first detailed observations of processes that control many astrophysical phenomena.

The next step will be to deploy a geosynchronous platform several thousand kilometers above the Space Station. At these altitudes, there are no day/night cycles, and solar viewing is uninterrupted. Scientists will be able to track the detailed evolution of solar phenomena across the entire solar disk. Instruments on the platform may be remotely controlled from the Space Station or the ground.

As solar physicists' understanding of the sun progresses, it will be very important to share information with scientists studying the atmosphere and the plasma environment enveloping Earth. Space Station will provide the first chance to make a coordinated set of measurements of the sun, the space plasma, and the atmosphere from low-Earth orbit. As solar physicists monitor events on the sun, plasma physicists and atmospheric physicists will measure the impacts closer to home. This will result in a valuable model of the workings of a star system, a model which can be applied to astrophysical systems throughout the universe. ■



Instruments on a proposed Solar-Terrestrial Observatory platform will be able to monitor events such as solar flares and subsequent effects on Earth's environment.

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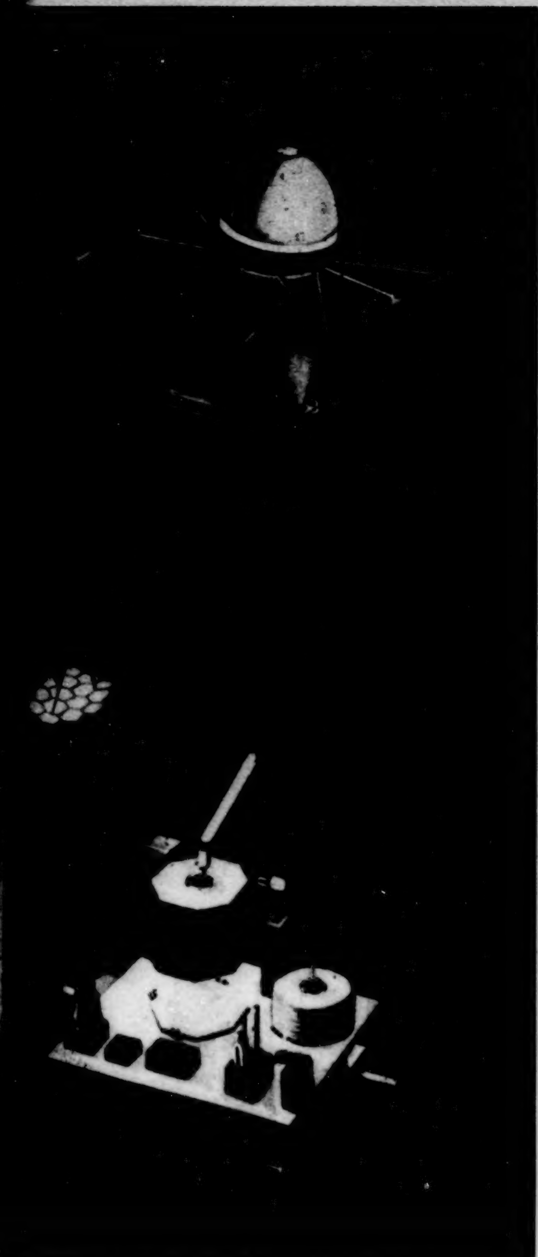

Solar Physics Investigations

OSS-1/STS-3	*Solar Flare X-Ray Polarimeter (SFXP)* *R. Novick, Columbia University, Columbia, Missouri*
	Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) *G.E. Brueckner, Naval Research Laboratory, Washington, D.C.*
Spacelab 2/51-F	*Coronal Helium Abundance Spacelab Experiment (CHASE)* *A.H. Gabriel, Rutherford and Appleton Laboratory, Chilton, United Kingdom* *J.L. Culhane, University College, London, United Kingdom*
	High Resolution Telescope & Spectrograph (HRTS) *G.E. Brueckner, Naval Research Laboratory, Washington, D.C.*
	Solar Optical Universal Polarimeter (SOUP) *A.M. Title, Lockheed Solar Observatory, Palo Alto, California*
	*Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)** *G.E. Brueckner, Naval Research Laboratory, Washington, D.C.*

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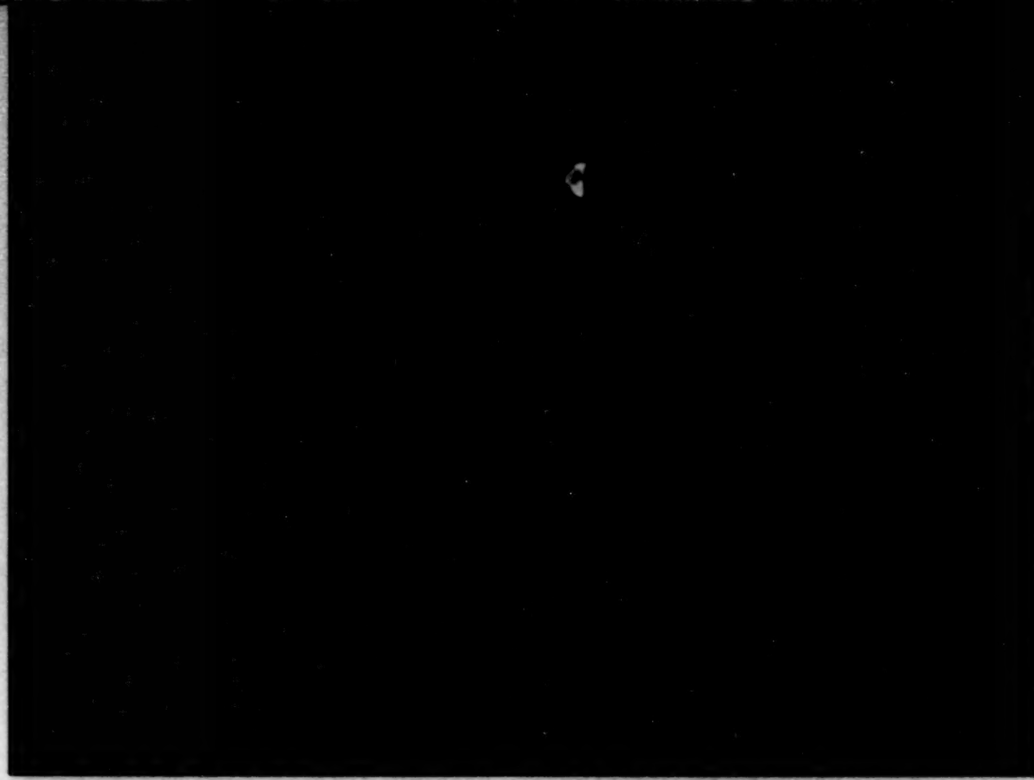
Chapter 5

Using Space as a Laboratory: Space Plasma Physics



Studies of plasma near Earth may help us understand the plasma environments around other planets and their moons.

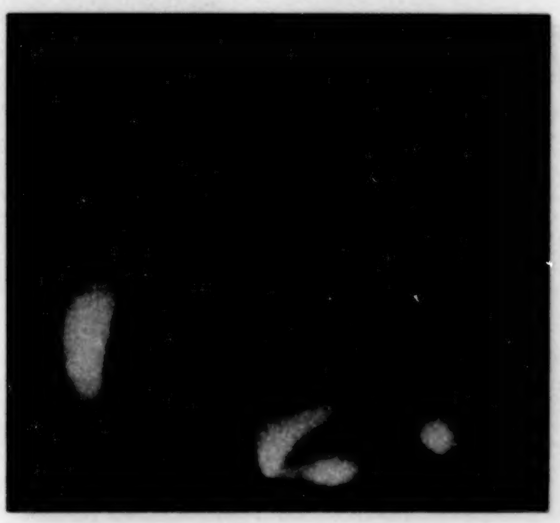
Earth's atmosphere varies with altitude, and its several regions have distinct compositions and physical properties. The ionosphere, where the gas is partly ionized or electrified, extends from approximately 60 to 1,000 kilometers (40 to 600 miles) above Earth's surface; it is an excellent place to study how electrified gases (plasmas) behave. Most of the universe is in the plasma state. By studying the space environment in Earth's neighborhood, we gain clues about processes around distant planets, stars, and other celestial objects.

Scientists have sent rockets and satellites to explore the ionosphere, and they have gathered data whenever and wherever auroras (the ghostly Northern and Southern Lights) and other plasma events occur naturally. However, it is impossible to create on the ground a laboratory as vast and variable as the ionosphere. To understand this complex environment, we must make space our laboratory.

As the Shuttle orbits Earth at altitudes of 240 to 400 kilometers (150 to 250 miles), it is immersed in ionospheric plasma. While in this environment, the Shuttle/Spacelab can be used to deploy small satellites and retrieve them, expose detectors directly to natural plasma, disturb the plasma with beams of energetic particles, and operate in coordination with ground-based facilities and other satellites. During a Shuttle/Spacelab mission, the ionosphere becomes a laboratory for studying processes that occur near Earth and throughout the universe, and the vehicle itself becomes an instrument for experiments. The space plasma environment is studied by three techniques: active experiments, in-situ probes, and remote sensing.

Active experiments introduce agents (particles, waves, chemicals) into the ionosphere to trace, modify, or stimulate the environment. The Shuttle itself stimulates the environment as it passes through the plasma, creating a wake and other disturbances. By carrying both active and passive probes, Spacelab functions as a laboratory and an observatory, simultaneously able to stimulate the space environment in a controlled manner and monitor the resultant effects.

In-situ probes are needed to diagnose the characteristics and changes in ambient plasma populations near the Shuttle. Spacelab has carried a variety of passive probes which operated independently or in concert with active experiments.



Scientists gather data from auroras and other natural plasma events.

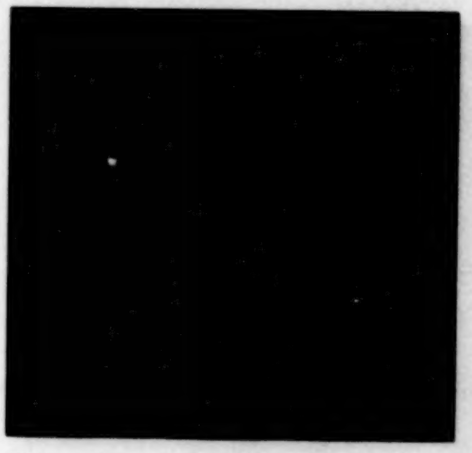
Remote sensors are used to detect the effects of active experiments or to study natural atmospheric phenomena at greater distances from the Shuttle. Emissions of light accompany many processes that are difficult to study from the ground because the atmosphere obscures them. On Spacelab, instruments have a global view and can detect faint light emitted by atmospheric chemicals, by energetic processes such as auroras, or by active experiments.

Active Experiments: Spacelab is ideally suited for active experiments. Instead of waiting for nature to perform, scientists can create artificial auroras, particle beams, plasma waves, and wakes. Ordinarily unseen magnetic field lines and wind patterns may become visible in clouds of color produced by chemical releases, enabling us to watch and photograph the form and motion of space plasmas.

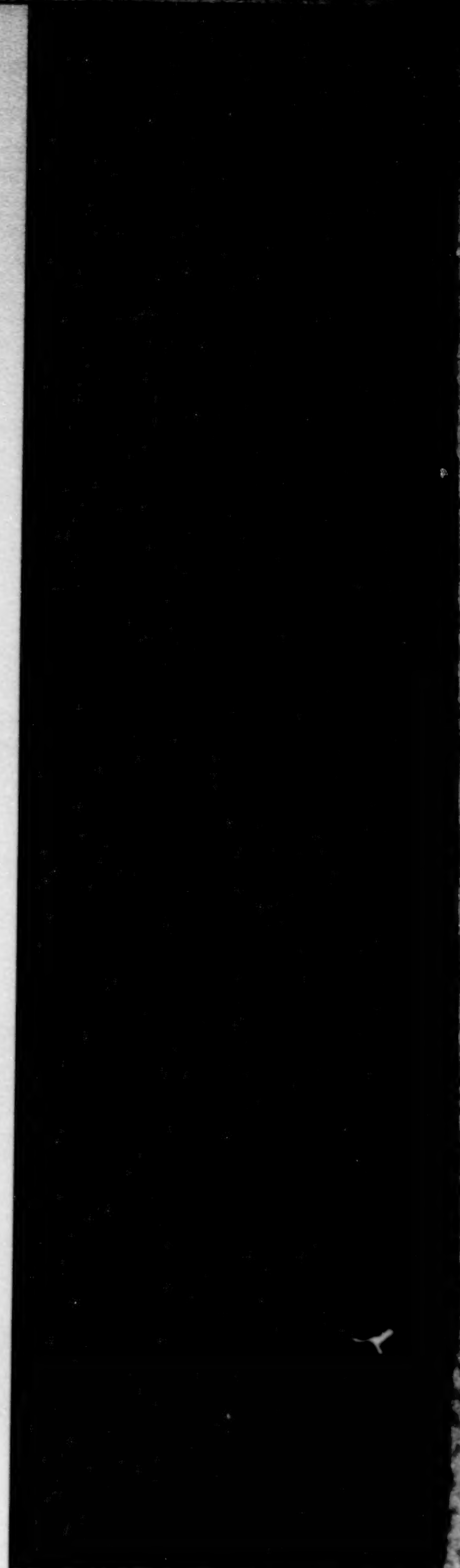
In active experiments, investigators introduce a known stimulus and measure the environment's response to test hypotheses about the natural processes of particle acceleration, wave and wind movement, chemical releases, and energy release. Three types of active experiments have been accomplished during Shuttle missions: particle beam and wave injections, wake and sheath generation, and chemical releases. Passive instruments for measuring changes in plasma conditions were necessary companions to all active experiments.

Beam and Wave Injection: Beam injection experiments help scientists trace the invisible electric and magnetic fields that envelop Earth. Electron beams emitted from Spacelab travel along magnetic fields. By measuring the paths of the beams, scientists can discover how particles are accelerated and guided in the plasma environment.

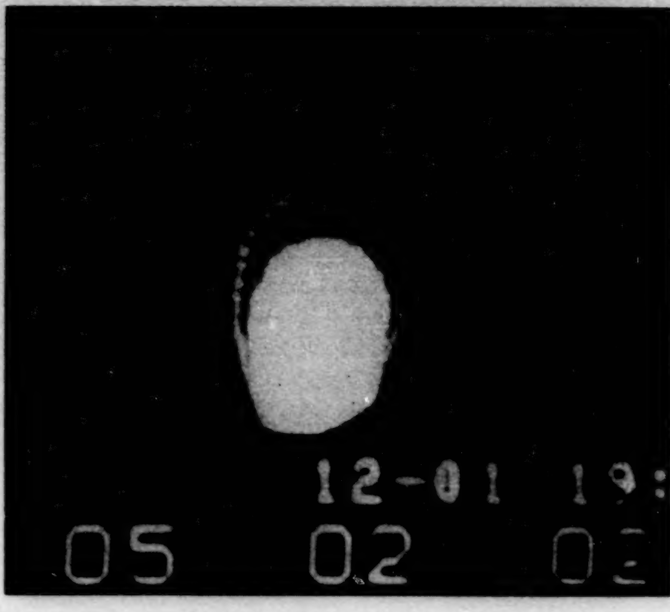
Waves are generated naturally in plasma by the constant mixing and flowing of plasmas and by sudden disturbances, such as lightning or particle beam injections. Thus, emitted particle beams or radio waves trigger wave motions in the natural plasma. Plasma waves are important mechanisms for transferring energy from one plasma regime to another, where it may be deposited, absorbed, or transformed and carried elsewhere. Comparisons of wave input and output yield information about energy exchange.



Electron beams emitted during the Spacelab 2 mission interact with natural plasma in the vicinity of the Shuttle.



In a laboratory, electron beam experiments are confined by walls; the Shuttle is making it possible for scientists to do similar plasma physics experiments in the vast, unconfined laboratory of space.



This computer image maps a plume of particles after an emission by the Space Experiments with Particle Accelerators (SEPAC).

Beam and wave injections are helping scientists understand processes such as auroras that occur when beams of particles from space collide with atmospheric particles around Earth's magnetic poles. These experiments also may reveal clues to particle beam activity detected in solar flares and in the vicinity of other planets (Jupiter and Saturn).

The Space Experiments with Particle Accelerators (SEPAC) flown on the Spacelab 1 mission used the Shuttle as a platform for active space plasma research. The investigation used a particle accelerator that could emit electron beams from 1,000 to 7,500 volts and up to 1.6 amps and a magnetoplasma dynamic arc jet which emitted pulses of argon ions. Several passive probes were carried to observe the shape of the beam and to measure wave and particle interactions.

When the electron beam accelerator was operated above current levels of about 100 milliamps, the character of the beam changed dramatically because of strong turbulence. The beam spread rapidly in space, and many electrons from the beam scattered back to the Shuttle, causing a bright glow on the surfaces and in the thin atmosphere surrounding the Shuttle. Indeed, the Shuttle actually charged positive as it sought to attract electrons from the ionsphere to balance the current shot forth in the electron beam.

The charge buildup on the Shuttle was neutralized momentarily by injecting a plume of neutral gas simultaneously with the electron beam. To the surprise of the investigators, the gas neutralized the charge instantly, and the vehicle charge remained neutral for several milliseconds after the simultaneous emissions. This indicates that injections of neutral gas may be an effective way to eliminate spacecraft charges.

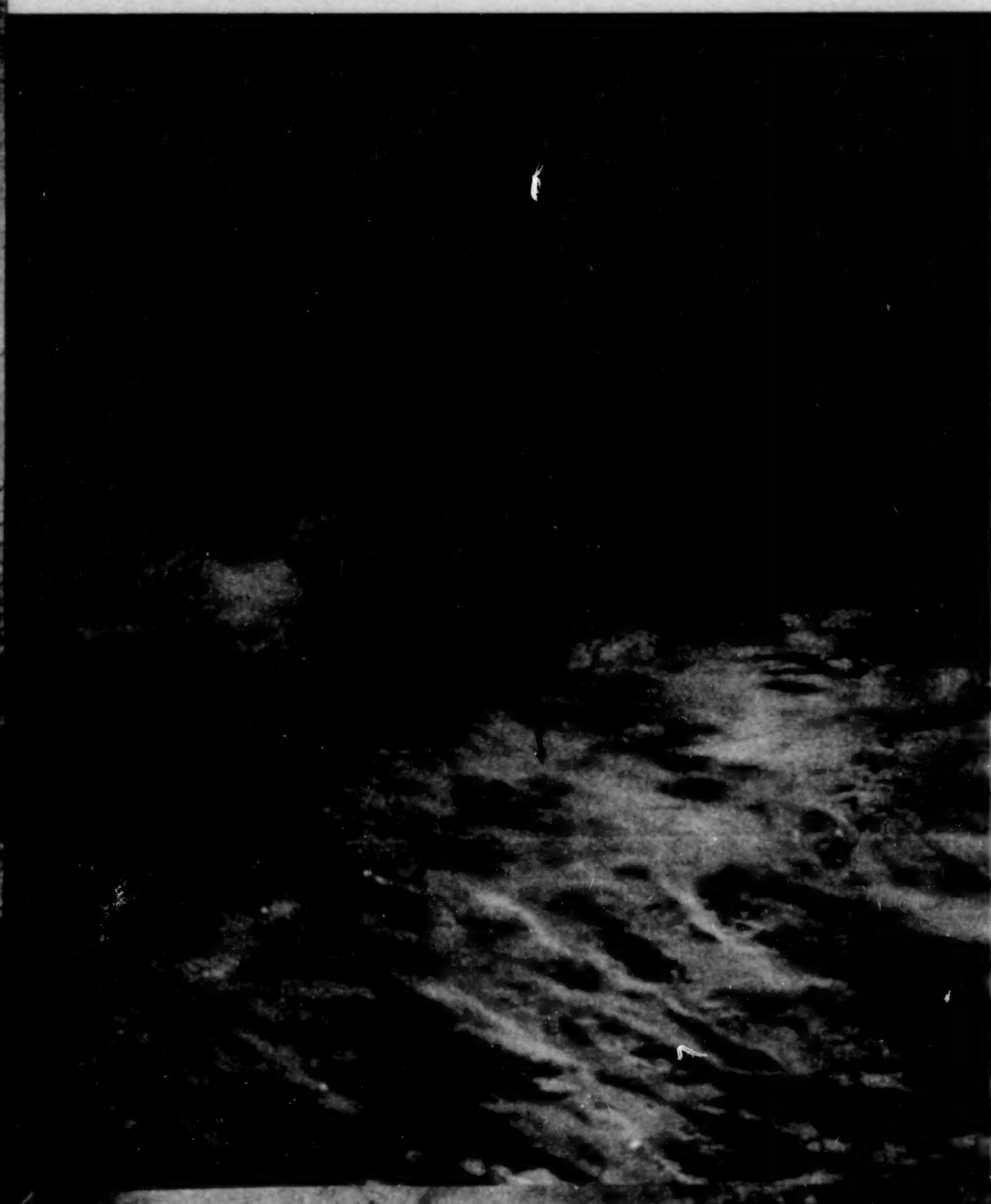
Another surprise was that during neutral gas injection, electron density increased, indicating that neutral atoms were being torn apart and converted into ions and electrons by interaction with the ambient ionospheric plasma. Passive detectors measured ionization 10 to 100 times greater than the ambient electron density. The instant reaction of these relatively benign neutral atoms with the natural space plasma is evidence that the ionosphere can become dynamic and turbulent. In addition, a plasma generator was used to inject pulses of ions and electrons which neutralized the Shuttle's electrical charging.

Other evidence of the strong beam-plasma interactions was observed by a joint experiment that used an electron spectrometer to measure modifications in electron populations. Spacecraft charging was observed, as well as processes that accelerated electrons to more than four times their injection energy.

Particle beams were also injected by the Spacelab 1 Phenomena Induced by Charged Particle Beams (PICPAB) experiment. An electron and ion accelerator mounted on a pallet generated beams while passive diagnostic instruments on the pallet and deployed through the Spacelab scientific airlock measured resultant effects. When the beams were injected, plasma wave activity was measured in the vicinity of the airlock, and the beams created several instabilities in the natural magnetic and electric fields. Changes in the electric and magnetic fields were also recorded during emissions by the other particle accelerator. There were large variations of the Shuttle/Spacelab charge with respect to the ambient plasma potential, and it took from a few milliseconds to several seconds after the beam was switched off for the vehicle potential to neutralize.

Spacelab 2 carried another beam-injection experiment, the Vehicle Charging and Potential Experiment (VCAP), which studied beam injections near the Shuttle and operated jointly with a deployed satellite so that the beams could be studied as they propagated further into space. (Both sets of instruments had an earlier trial flight on the OSS-1/STS-3 mission.) An electron generator mounted on the pallet emitted electrons in a steady stream to create beams and in pulsed modes to create waves of known frequencies. The maximum beam current was 100 milliamps and its energy was 1,000 electron volts, resulting in a beam power approximately equal to that of a 100-watt light bulb. The Vehicle Charging and Potential Experiment also studied how the beam injections charged the Shuttle and affected plasma in its vicinity.

For the joint experiments, the Plasma Diagnostics Package (PDP) was deployed as a free flyer about 300 meters (0.25 miles) away from the Shuttle. The satellite consisted of complementary instruments for simultaneous measurements of plasma characteristics such as magnetic and electric fields, particle distributions, radio waves, and plasma composition, density, and temperature. During the free flight, the crew completed intricate maneuvers to align the satellite and the Shuttle along the same geomagnetic field line, like beads on an imaginary string. At the moment the Shuttle



The Plasma Diagnostics Package (PDP) was released as a free flyer to measure plasma characteristics away from the Shuttle.

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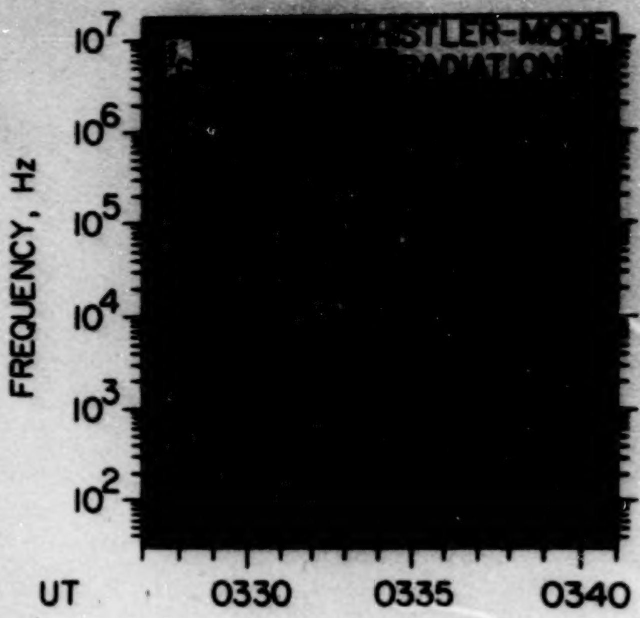


This radio spectrogram from a PDP receiver shows that an electron beam interacted with plasma to generate a whistler radio emission. This experiment duplicated a natural phenomenon; similar whistler emissions are often generated by natural electron beams along auroral field lines.

crossed the magnetic field, an electron beam was emitted, and the satellite measured the characteristics of the beam as it traveled along the magnetic field and spread into the ionosphere.

The spectrum of waves from the beam appears as an intense broadband emission. An unusual feature of the beam may be caused by whistler radiation, plasma waves that travel at specific angles to magnetic fields. The whistler radiation seen by the PDP near the electron beam is analogous to the auroral hiss radiation seen by satellites passing over the Earth's auroral zones. This sort of beam-to-wave energy conversion is a fundamental process responsible for radio emissions from other planets and astronomical systems.

Another time when the satellite and Shuttle were aligned along the magnetic field, the beam was pulsed to create plasma waves similar to low-frequency radio signals. The satellite measurements during the beam and wave injections indicate that the beam heated ions in the natural plasma and created turbulent motion, density variations, and strong electric fields. Since similar processes occur during auroras and magnetic storms, these beam injection experiments strengthened the link between active experiments and the physics of auroral beams.

The joint PDP-VCAP experiments on Spacelab 2 were the culmination of a series of earlier experiments. The first joint measurements to study the effects of an electron beam on the space environment, and vice versa, were performed in a large ionospheric simulation chamber on the ground. These preliminary experiments provided valuable experience in operating both sets of instruments and also in selecting suitable operating modes for the electron beam. For the OSS-1 mission, planners drew upon the chamber test experience to improve the flight plan for PDP operations on the remote manipulator arm. When OSS-1 results proved to be of great interest to space plasma physicists, the next logical step was proposed: to conduct joint experiments and study beam effects over a greater range beyond the 12-meter (40-foot) reach of the arm. Releasing the PDP as a free flyer during the Spacelab 2 mission was already planned; the VCAP experiment was added to the payload to follow up on

Space experiments with the PDP were the culmination of years of testing and planning in ground-based plasma laboratories. Here in the Johnson Space Center plasma chamber, the PDP is engulfed by a glowing column of energetic electrons emitted by the electron generator that was flown with the PDP on two Shuttle missions.

Plasma distributions were mapped as the manipulator arm moved the PDP around the Shuttle.

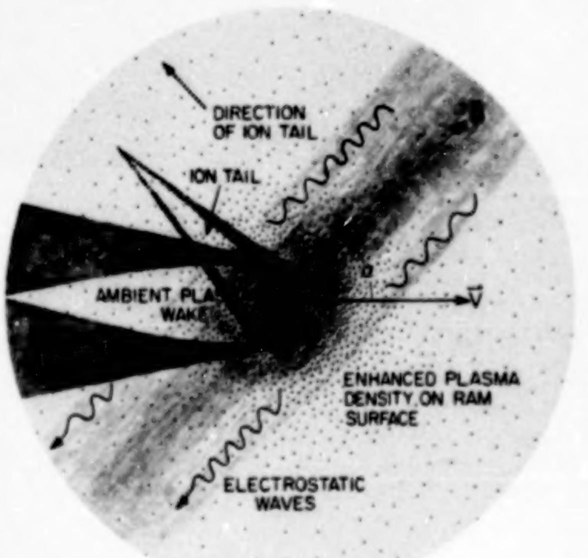
the OSS-1 success and study beam effects over a greater distance. This ongoing iteration of an experiment in light of cumulative experience is one of the primary advantages of the Shuttle for science; it allows scientists to refine their objectives, equipment, and procedures through reflights in much the same way as they perfect experiments by repetition on the ground.

Wake and Sheath Generation: As it travels through space, the Shuttle affects the density, temperature, and electrical properties of the surrounding plasma. An electric field sheath develops around the vehicle and, like a boat, the Shuttle creates a wake in the plasma. The wake is depleted of plasma as the Shuttle collides with and displaces the gas, and various instabilities occur as the wake region is refilled with plasma.

Many other celestial objects such as moons, asteroids, and comets also travel through gases of charged particles. Wake and sheath experiments can help scientists determine flow patterns around natural bodies, such as the moon Io that passes through Jupiter's plasma environment.

Wake and sheath experiments aid in evaluations of the Shuttle's effect on Spacelab investigations which study a medium that is being disturbed by the vehicle that carries them. This knowledge is pertinent for planning future experiments, interpreting data, and designing other large space structures and observatories that also will be traveling through the ionosphere.

Experiments in simulation chambers and a few remote observations of plasma activities around comets, planets, and moons led to theories about large body interactions with plasmas. The PDP's first flight on a pallet in the Shuttle payload bay and on the Remote Manipulator System (RMS) during the OSS-1 mission gave scientists a chance to make direct measurements around a large body moving through space. These measurements yielded several discoveries: a large gas cloud enveloped the Shuttle, trailing out to unknown distances; a broadband electrical noise was emitted around the Shuttle; and ion and electron interactions occurred between ambient plasmas and molecules released from Shuttle water dumps and thruster firings. The plasma disruptions created by the Shuttle were more complex than expected, and another mission



The gas cloud given off by the orbiter produces reactions that modify the density of nearby plasma. Ions created from a charge-exchange reaction with the plasma produce electrostatic waves that are evident at more than 300 meters (0.25 miles) from the orbiter along magnetic fields. The plasma wake of the Shuttle results in an ion tail similar to the tails of comets.

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was warranted to extend observations.

To continue the inquiry begun on the OSS-1 mission, the PDP was flown on the Spacelab 2 mission. This time, it was moved about on the RMS out to distances of 12 meters (40 feet) to map the surrounding plasma environment. The Shuttle made several intricate maneuvers so that the satellite could study diverse plasma effects around the Shuttle. Measurements indicated that the thermal ion distributions around the spacecraft are much more complex than predicted. Frequently, an unexpectedly intense background level of ion current due to incoming hot ions was measured. Surprisingly, the ions often appeared to change energies, an indication of high ion temperatures and turbulent plasma activity. These effects have not been observed by satellites and rockets; the new observations demonstrate the significant impact of a large, gas-emitting space vehicle like the Shuttle on the ionosphere.

As on the prior mission, the satellite instruments again detected the emissions from material outgassing, thruster firings, water dumps, and a cloud of neutral gas that expanded away from the Shuttle. The gaseous cloud modified the ionosphere at large distances through chemical interactions between ions and neutral atoms. Water vapor was detected in the immediate vicinity of the Shuttle out to several hundred meters. These contaminants were especially dominant in the Shuttle's wake, and natural plasma ions of nitrogen (N_2+), nitric oxide ($NO+$), and oxygen ($O+$) were depleted. These contaminants interfere with measurements of natural plasma made from the Shuttle payload bay.

The PDP never sampled undisturbed natural plasma because the ionosphere was perturbed out to the distance covered by the PDP during its free flight. Investigators are comparing the Shuttle to a comet, which creates a deep wake and turbulence as it moves through plasma. The gas cloud enveloping the Shuttle is large enough to be

The top panel of these two spectrograms shows the angle of diffracted particles as they fill the wake left by the Shuttle. The bottom panel shows the distribution of ion energy over time. By studying intensity changes at different angles, investigators are trying to determine the physical processes occurring as the particles refill the wake. Similar processes may occur in the wakes of celestial bodies moving through space.

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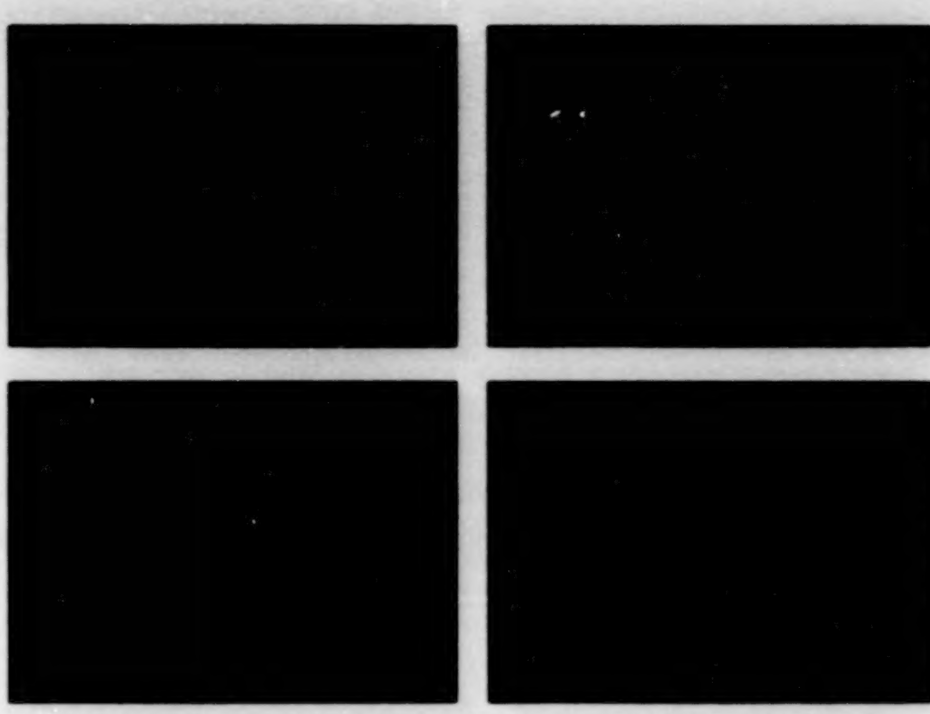
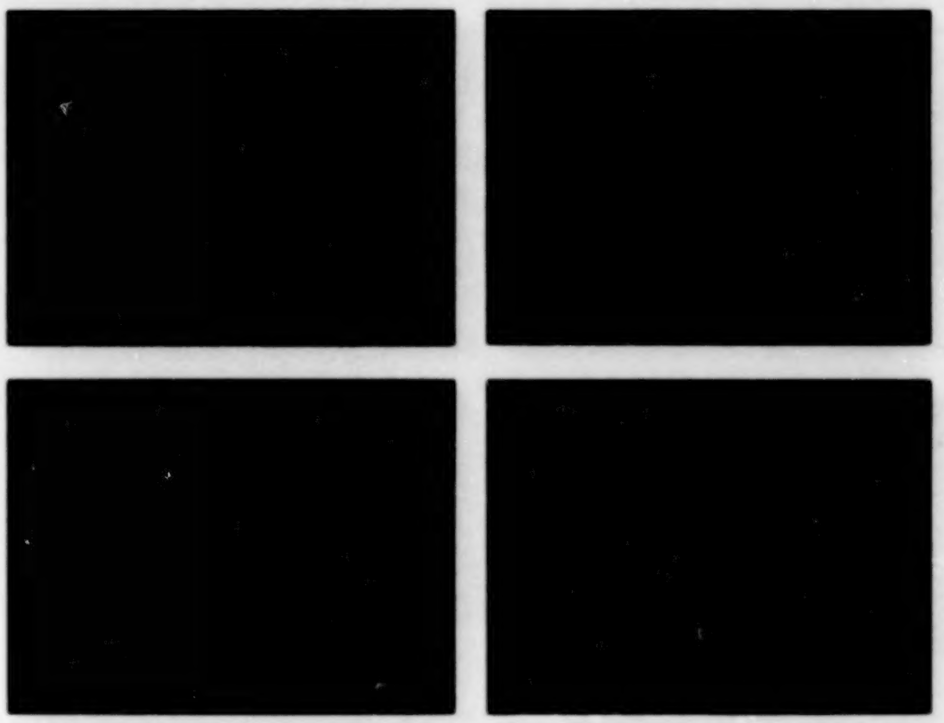
similar to a comet's surrounding cloud; also, the Shuttle appears to release molecules, such as water, that react with ions from the natural plasma and form new molecular species. This may be similar to the process by which comets react with ions from the ambient plasma to create their long tails.

An attempt to map the multiple ion streams and wake around the Shuttle yielded fascinating observations of plasma flows, density variations, and turbulence associated with the wake. With the plasma satellite extended 10 meters (33 feet) on the arm, the Shuttle performed a roll maneuver, sweeping the satellite through the wake. Measurements obtained during these maneuvers indicated that ions from the ambient ionosphere were accelerated into the wake from above and below the vehicle.

Investigators are trying to determine how particles are accelerated rapidly enough to refill the plasma void in the Shuttle's wake. Various explanations are under consideration. One possibility is that a strong electric field, which is created by density differences between the depleted wake and the ambient ionosphere, accelerates the ions into the void. This expansion process has been observed in laboratory experiments but never in a natural plasma environment. Plasma physicists believe that it may be a common process around large natural celestial bodies moving through various types of space plasmas.



This series of computer-enhanced optical images shows the effects of a Shuttle engine firing. The visible emission results from the neutralization of ionospheric ions and electrons by carbon dioxide in the Shuttle's exhaust. As the plasma returns to normal, the red airglow fades.



The Millstone Hill radar antenna mapped variations in electron density during the plasma depletion experiment. These panels show pre-event conditions (a) and the resultant perturbations at 14 minutes (b), 40 minutes (c), and 107 minutes (d) after the Shuttle thruster firing.

Chemical Releases: Chemical releases in the ionosphere often result in luminous particle interactions that "paint" invisible magnetic fields, currents, and waves in vivid color. Hidden features of the structure, chemistry, and dynamics of the atmosphere are revealed by visible movements of vapors and plasma.

One Spacelab 2 investigation took advantage of chemicals that the Shuttle routinely releases when thrusters are fired to maintain or change altitude: exhaust consisting mainly of water vapor, carbon dioxide, and hydrogen. The effects of these releases are temporary and are not detrimental to the environment, but they do cause some interesting physical and electrical changes in the ionosphere.

The exhaust triggers chemical reactions that cause electrons to combine with ions in the upper atmosphere, leaving temporarily depleted plasma areas or "holes." The most visible effect of the holes is a faint red airglow emission associated with carbon dioxide molecules. Radar and radio measurements at ground observatories can detect other traits of these holes, such as elevated electron temperature, reduced electron concentrations, drifts of nearby plasma into the hole, and disrupted or enhanced radio wave propagation.

The Shuttle's ability to fire the engines to release exhaust at specific times and locations allowed Spacelab 2 scientists to monitor the areas of depleted plasma from three separate observatories on the ground. There were two nighttime engine burns during which optical emissions could be monitored. Within seconds after the burn over the Millstone Hill Incoherent Scatter Observatory in Westford, Connecticut, the red airglow emission at 630 nanometers increased sharply, reached a maximum 3 minutes later, and gradually decayed for 10 to 15 minutes. The airglow cloud grew to 300 kilometers (186 miles) in diameter and then faded back to normal. Radar data indicated that electron density was depleted and the hole spread in altitude and latitude for one hour. During a relatively smaller daytime exhaust release over the same site, radar data indicated that electron densities were reduced, confirming that even small releases affect the ambient plasma.

The goal of another engine burn, over the University of Tasmania low-frequency radio observatories in Hobart, Tasmania, was to test the concept of conducting low-frequency radio astronomy through an artificially created window in the ionosphere. To the disappointment of astronomers who study radio emissions in an effort to learn about distant celestial objects, radio waves in the band less than 3 megahertz are blocked by the ionosphere. After the burn over Hobart, electron densities were reduced by 20 to 30 percent, and cosmic signals at 1.7 megahertz were received through the plasma hole. The experiment thus succeeded in demonstrating that plasma depletions may indeed open new astronomical windows.

Complementing the ground-based observations, measurements made by instruments aboard the Shuttle indicated that ambient plasma activity was enhanced for several minutes after each thruster firing. Depletions in plasma density, airglow enhancements, increases in turbulence, and variations in spacecraft potential were recorded.

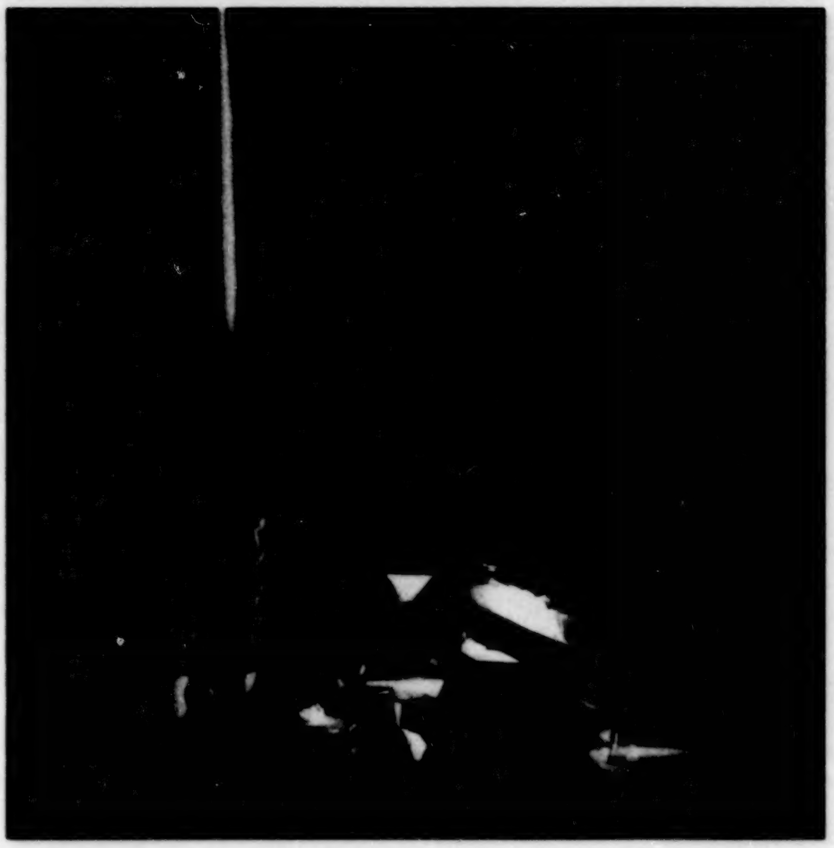
Passive Monitors: Through active experiments and on-site diagnostic instruments, space scientists have learned a great deal about how the natural plasma environment acts when disturbed. However, Spacelab gives scientists another advantage: a global view of the atmosphere that is not possible from the ground. The Shuttle/Spacelab serves as an excellent platform for atmospheric observations.

From space, the light emissions from the atmosphere make it a giant television screen that shows changing chemical reactions. Even though these events occur far from the Shuttle, sensitive onboard instruments can make images of the tell-tale light emissions associated with chemical reactions.

The Atmospheric Emission Photometric Imager (AEPI) flown on Spacelab 1 was designed to study global patterns in magnetic fields and other features occurring naturally in the atmosphere. Images of the

A photometric imaging experiment was flown on Spacelab 1 to study faint natural and artificial atmospheric emissions. This optical image reveals sunlit ionized magnesium in Earth's atmosphere.

Earth's magnetic field in the vicinity of the Shuttle was computed and superimposed over the magnesium emission seen at 100–200 kilometers (60–125 miles) altitude. Since magnesium emissions appear to align with the magnetic field, they can be used as a visible tracer of magnetic fields.



The glow that surrounds the Shuttle as it travels through space continues to mystify plasma physicists as well as scientists in other disciplines.

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atmosphere were produced by two low-light-level television cameras with special lenses and filters. The filters help the instrument detect faint emissions from metastable oxygen, magnesium ions, and other atmospheric elements in the 200 to 750 nanometer spectral region.

Magnesium ions deposited at altitudes of 100 to 200 kilometers (60 to 125 miles) by meteors burning up during entry were imaged by AEPI as they scattered sunlight. By comparing the images to magnetic field data taken at the same time, investigators were able to show that the magnesium clouds were aligned along the magnetic fields for 1,600 to 2,400 kilometers (1,000 to 1,500 miles). Now scientists can use magnesium deposits to trace magnetic fields.

Observations also were made of atmospheric airglow created as molecules react with sunlight and of the glow associated with the Shuttle. It has been suggested that hydroxyl (OH) is a candidate species for producing the troublesome Shuttle glow which may interfere with some astronomical observations. However, hydroxyl may not be the dominant species involved in Shuttle glow, because it was detected in photographs of Earth's airglow but was absent in photographs of Shuttle glow. The glow has been studied on other missions by scientists from different disciplines who have proposed various theories concerning the glow. Other candidates that may be involved in the glow reaction include nitrogen dioxide (NO_2), carbon monoxide (CO), and nitrogen (N_2).

From Spacelab, scientists have an unusual view of the aurora which occurs in an altitude range of approximately 60 to 1,000 kilometers (40 to 600 miles). To date, most views of the aurora have been from the ground or from satellites in orbits far above the aurora. The orbit and inclination of the Spacelab 3 mission gave scientists a

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These auroral photographs taken from the Space Shuttle show how a rare red emission from atomic oxygen (630 nanometers) changes as it dances across the atmosphere, reaching an altitude of more than 450 kilometers (280 miles). The uniform white band along the horizon is the atmospheric airglow layer at 95 kilometers (60 miles) altitude.

closer, side view of the aurora. The Shuttle's cameras were used to record 5 hours of videotapes and 274 still photographs. In conjunction with orbital motion, the video and photographs were taken so that they overlapped and could be viewed stereoscopically.

The aurora is not just a glowing spot in the sky; it is a bright oval encircling the polar region. Both Earth's magnetic and electric fields modulate the aurora to produce the bright curtain and ribbon-like forms as well as the dim diffuse aurora. The aurora is the only natural visible manifestation of the magnetosphere, and by studying changes in its form and motion, scientists can infer changes in the patterns of Earth's electromagnetic field.

As light shows danced across the polar cap of the Southern Hemisphere, Spacelab 3 scientists recorded features that had never been seen before, including the first views from outside the atmosphere of thin horizontal layers of enhanced aurora. The layers, once thought to be rare, were recorded on two of the three Shuttle passes over the aurora. This first observation of enhanced aurora from space eliminates concerns that the ground-based observations might have been optical illusions caused by atmospheric refraction.

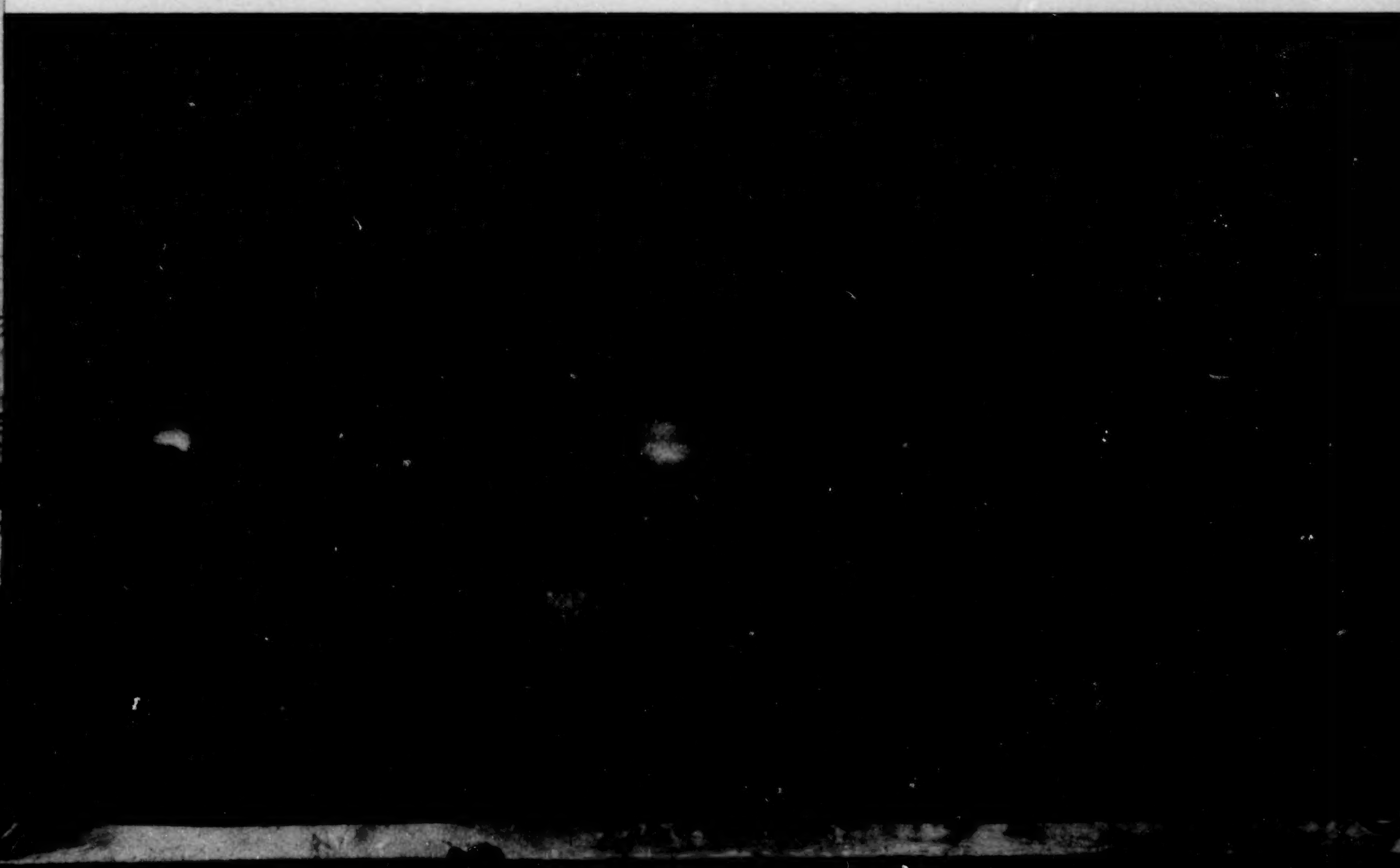
Also for the first time, thin vertical layers were observed in diffuse auroras.

This observation is possible only from space, ideally in near-Earth orbit, because diffuse auroras cover a wide range of latitudes; when viewed from the ground or from above by satellites, they appear as a uniform glow. From the vantage point of the Shuttle, scientists got an edge-on view of diffuse auroras and could see the various thicknesses and layers within. The mission resulted in an extensive catalogue of known auroral features, including a collection of images of tall red rays extending over a wide geographical range. Scientists are using these images to see how auroral features vary with location over Earth.

An Unbounded Laboratory: To fully understand the space plasma environment enveloping Earth, plasma physicists must join with solar and atmospheric physicists to study the integrated solar-terrestrial system. Solar-terrestrial physics encompasses the entire sun-Earth system, including the detailed study of solar processes, the relationship between changes at the sun and resulting changes in Earth's magnetosphere and atmosphere, and the detailed physics of the Earth's magnetosphere/ionosphere/atmosphere system. The solar observations and radiation measurements, active space plasma experiments, and atmospheric and auroral observations of Spacelab 1, Spacelab 2, and Spacelab 3 are major steps in studying the integrated solar-terrestrial system.

Scientists are using their Shuttle/Spacelab experience to plan research for the Space Station and other observatories. The Space Station offers investigators a laboratory to continue the exciting manned research and observations initiated on the Shuttle/Spacelab. Some instruments will be attached to the station, making possible real-time observations of the sun and coordinated active experiments. Scientists in

The first observations from space of enhanced auroras were made during the Spacelab 3 mission. The thin band of light parallel to Earth's horizon is an edge-on view of the airglow layer at 95 kilometers (60 miles) altitude. A rayed auroral arc just above the airglow layer bends inward and passes under the Shuttle in the foreground. The rays in the arc extend upward approximately 60 to 200 kilometers (37 to 124 miles). A very thin band of brighter enhanced auroral emission less than 2 kilometers (1.2 miles) high runs through the aurora near the base of the rays.



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Scientists watched images of the aurora that were recorded and transmitted during Spacelab 3.

space and on the ground will be able to coordinate observations of important events, such as solar flares or magnetic storms, and track effects as they propagate from the sun to Earth's magnetosphere and atmosphere.

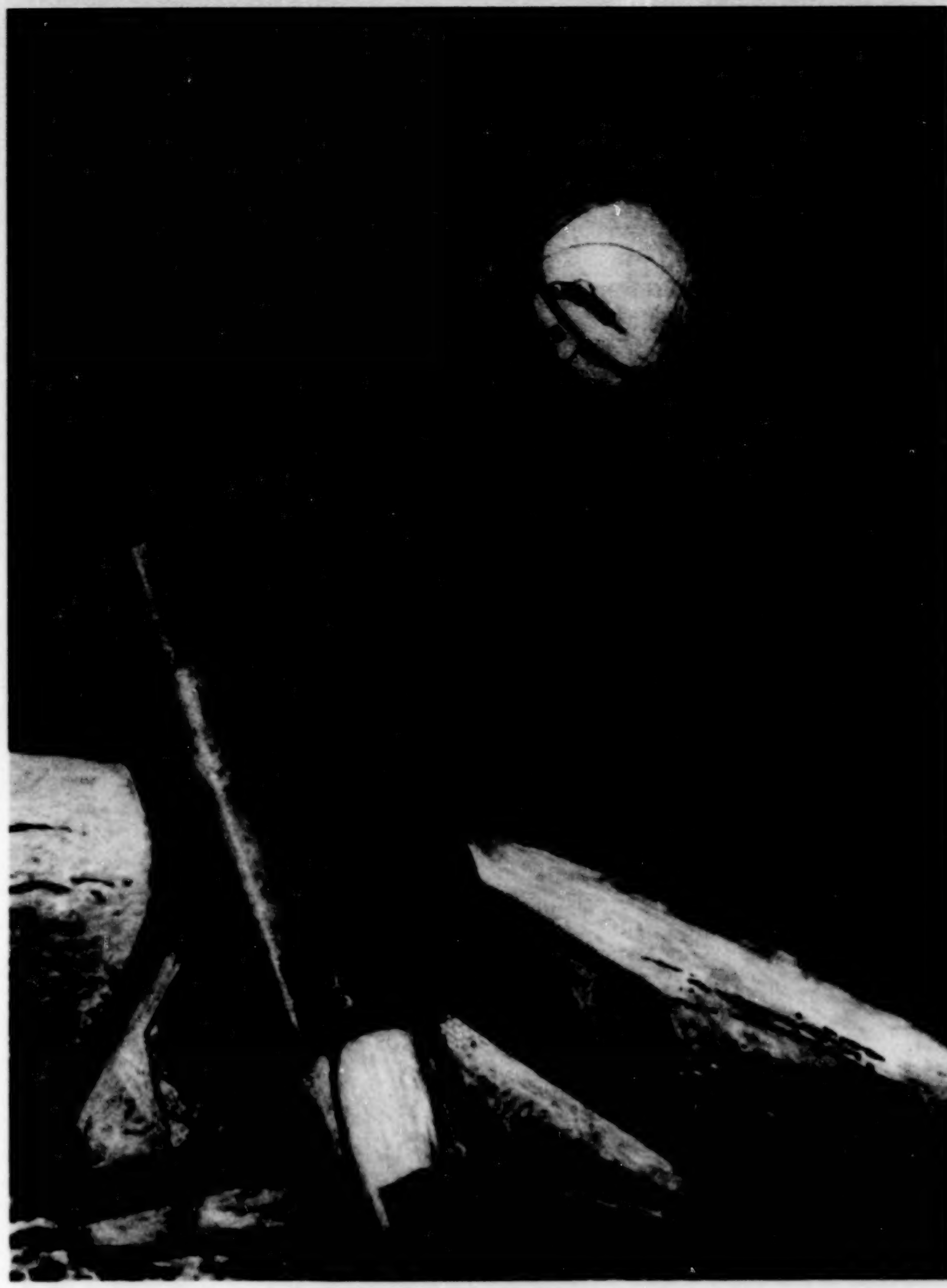
With the close interaction of well-trained scientist-crewmembers, more elaborate active experiments similar to those achieved aboard Spacelab 2 will be accomplished. Instruments on the Space Station, free-flying and tethered satellites, the Shuttle, and orbital platforms can make thorough simultaneous measurements of controlled perturbations of space plasma.

Plasma physics studies will continue with two major facilities now being planned. The Space Plasma Laboratory will incorporate several proven experiments, such as the Space Experiments with Particle Accelerators (SEPAC) and the Atmospheric Emissions Photometric Imager (AEPI) from Spacelab 1 and the Plasma Diagnostic Package (PDP) from Spacelab 2, as well as new instruments such as a special pair of extremely long whip antennas to transmit very low-frequency radio waves into the magnetosphere. The Space Plasma Laboratory instruments will probe the invisible cocoon that shelters our world from deep space. The Tethered Satellite, built by the United States and Italy, will study plasma phenomena by trolling an instrument package from the Shuttle through the atmosphere.

Since solar-terrestrial phenomena affect the entire Earth, the international cooperation of the Spacelab era must continue aboard the Space Station and in other research on co-orbiting and polar platforms. NASA has plans for the Solar-Terrestrial Observatory and the Earth Observation System, both of which will help us study the integrated sun-Earth system. Instruments aboard platforms will be able to make global observations at varying local times, altitudes, and latitudes. This is necessary for tracking events as they occur around the world and for mapping atmospheric constituents and conditions. Besides global coverage, the platforms will provide continuous viewing of the sun and Earth and its magnetosphere and atmosphere. This will allow scientists to monitor events as they evolve and observe conditions during different solar cycles.

The Space Station along with co-orbiting platform observatories will further research by offering manned operations, large and complementary instrumentation, on-orbit calibration and repair, deployment and retrieval of subsatellites, and a data system to bring all the information together. When we establish a permanent presence in space, we will have a vast laboratory at our disposal. ■

Scientists use the data from space to characterize the Earth's plasma environment and interpret the results of active experiments there.



Shuttle/Spacelab missions provide opportunities for scientists to gain valuable experience in space experimentation and formulate important questions to be answered by long-term Space Station experiments. In this artist's concept, the Tethered Satellite System studies the plasma surrounding Earth.

Space Plasma Physics Investigations

OSS-1/STS-3	*Plasma Diagnostics Package (PDP)* *S. Shawhan, University of Iowa, Iowa City, Iowa*
	Vehicle Charging and Potential Experiment (VCAP) *P.M. Banks, Stanford University,* *Stanford, California*
Spacelab 1/STS-9	*Atmospheric Emission Photometric Imaging (AEPI)* *S.B. Mende, Lockheed Solar Observatory* *Palo Alto, California*
	Electron Spectrometer *K. Wilhelm, Max Planck Institute* *Stuttgart, Germany*
	Magnetometer *R. Schmidt, Academy of Sciences, Vienna, Austria*
	Phenomena Induced by Charged Particle Beams (PICPAB) *C. Beghin, National Center for Scientific Research* *Paris, France*
	Space Experiments with Particle Accelerators (SEPAC) *T. Obayashi,* *Institute of Space and Astronautical Sciences* *Tokyo, Japan*
Spacelab 3/51-B	*Auroral Imaging Experiment* *T.J. Hallinan, University of Alaska* *Fairbanks, Alaska*
Spacelab 2/51-F	*Plasma Depletion Experiments* *M. Mendillo, Boston University* *Boston, Massachusetts, and* *P.A. Bernhardt, Los Alamos National Laboratory* *Los Alamos, New Mexico*
	*Plasma Diagnostics Package (PDP)** *L.A. Frank, University of Iowa, Iowa City, Iowa*
	*Vehicle Charging and Potential Experiment (VCAP)** *P.M. Banks, Stanford University* *Stanford, California*

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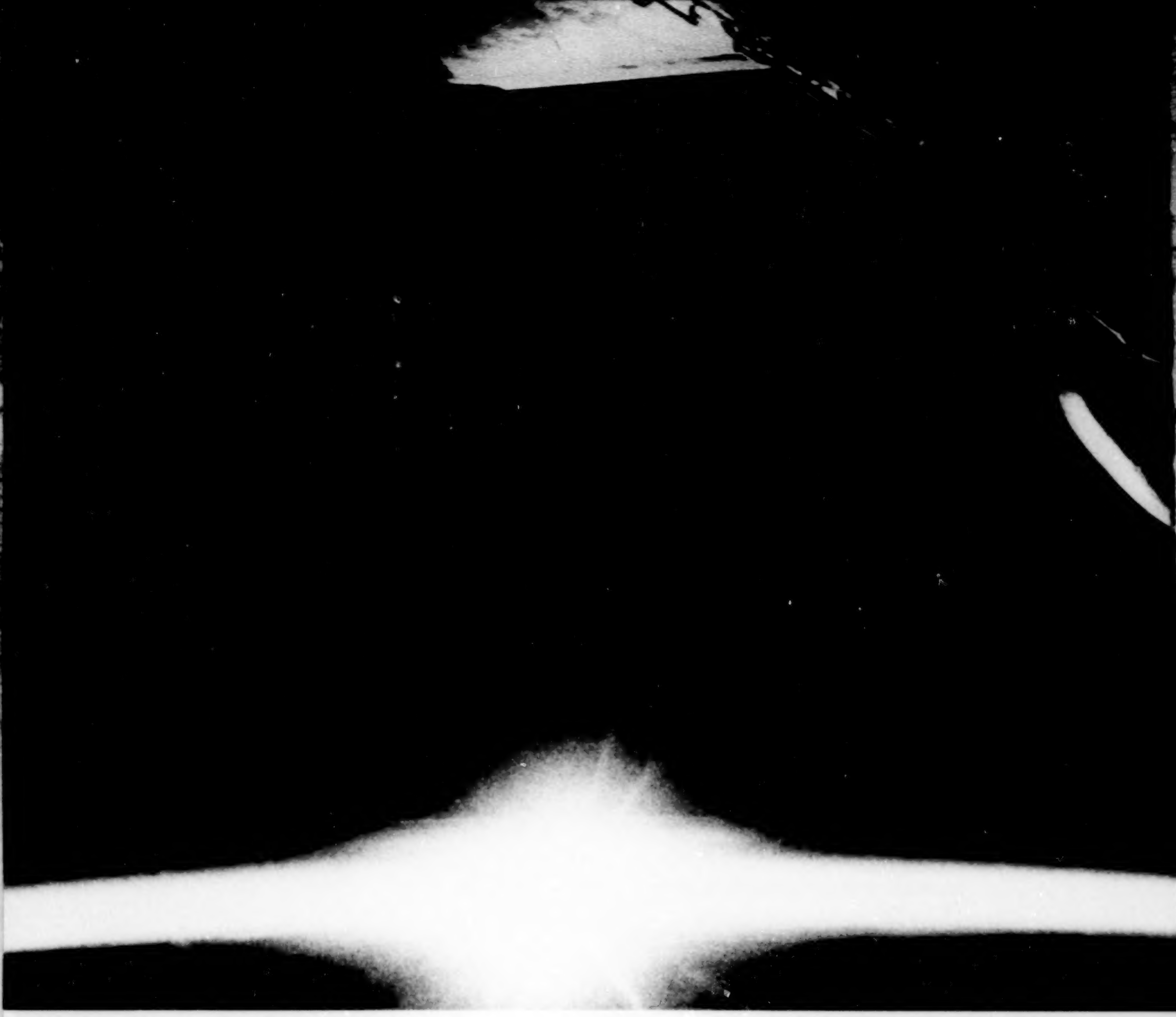

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Chapter 6

Sampling the Atmosphere: Atmospheric Science

Present knowledge of the atmosphere is immense compared to what we knew when the space age began three decades ago, but what we have yet to learn is still great. Moreover, we do not fully understand the roles we play in altering our atmosphere as we burn fossil fuels, use spray cans, and test nuclear weapons. Scientists worry about a multitude of factors that may turn our planet into a hothouse or an icebox.

The atmosphere is far more than oxygen and nitrogen; that familiar mix is roughly constant only to an altitude of about 100 kilometers (60 miles). As temperature changes with altitude, the pace at which some chemical reactions occur changes, and intensified sunlight causes new reactions like the splitting of oxygen molecules and the formation of ozone. Above this homosphere is the heterosphere where the chemical ratios change radically with altitude. Chemicals considered to be trace compounds are present at higher altitudes in greater ratios, although the total is still small.

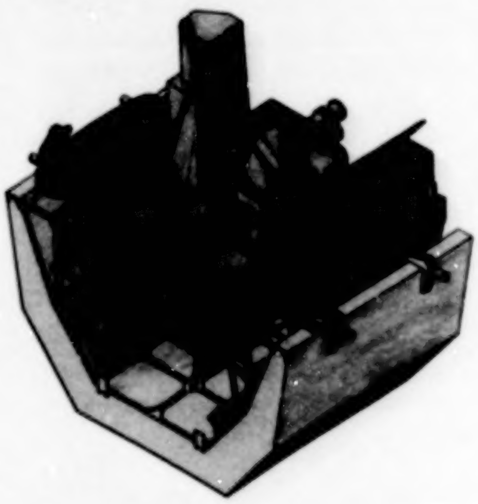
Atmospheric chemistry, driven by light and a bewildering array of products which themselves modulate the light passing to Earth, becomes more complex and our understanding becomes less certain. Eliminating that uncertainty requires a global view and an inventory not only of the relative abundance of chemicals at various altitudes in the atmosphere but also of their energy states, which dictate the reactions in which they may take part.

Atmospheric chemistry is a complex, interactive process with seemingly small changes leading to extensive chain reactions. When an atom captures a photon of the right wavelength (i.e., energy), its energy state is raised. Usually within millionths or thousandths of a second, the photon is released as the atom returns to its ground state. The wavelength of this

Chemical constituents and reactions change with altitude in different atmospheric layers.

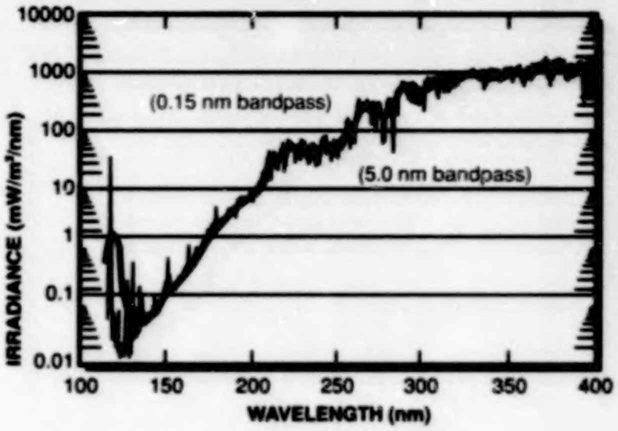
emitted photon is a unique atomic or molecular signature. With such spectral signatures, the presence and energy states of chemicals can be detected at great distances. Spacelab has carried several instruments that have detected these signatures and started detailed analyses of our atmosphere's energy, chemistry, and movement.

The Shuttle and Spacelab offer atmospheric scientists a platform for global viewing over a broad latitude and altitude range. From this well-situated observatory, it is possible to make a complete chemical inventory of the different atmospheric regions and study the entire atmosphere as a system. Larger, more capable instruments can be carried on the Shuttle than on other satellites, and the Shuttle's resources (power, telemetry, crew) support advanced observational techniques. A variety of experiments to date proved the merits of the Shuttle and Spacelab as host observatories for atmospheric imaging and spectral measurement devices.



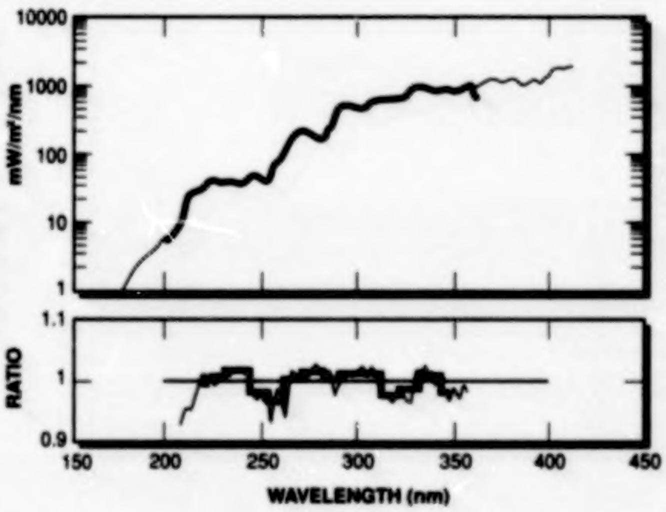
This drawing depicts large instruments flown on Spacelab 1 for atmospheric and plasma physics research. Larger, more capable instruments can be carried on the Shuttle than on other satellites, and the Shuttle's power and data processing support advanced observation techniques.

Energy: As the sun warms Earth, it prompts a chain of chemical reactions in the middle and upper atmosphere. These reactions change the transparency of the atmosphere, causing other changes at lower altitudes; greater fluxes of damaging ultraviolet radiation may pass to the ground, or infrared radiation (heat) emitted by the ground may be trapped rather than emitted, as in a greenhouse. The first concern is the total energy flow since life on Earth is so dependent on the constant sun emitting energy within a narrow range. Even a 0.1 percent shift in either direction could have a noticeable effect on the average temperature of the Earth and hence its climate. Yet measurements made to date vary by as much as 5 percent because of differences among and within instruments. Since the atmosphere is an unpredictable filter, these measurements can be made accurately only from orbit.



The Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) measured solar ultraviolet output in the wavelength band from 120 to 400 nanometers. The blue line records high resolution measurements, and the red line marks low resolution measurements.

For the first time, solar ultraviolet radiation measurements by two independent instruments agree within a few percent. The thin black line on the upper part of the chart is the Spacelab 2 SUSIM spectrum and the thick red line is the Spacelab 1 Solspec spectrum. Both were made at 10 nanometers resolution.



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The Solar Constant (SolCon) and the Active Cavity Radiometer (ACR) instruments are designed to monitor the total solar radiation output. Each uses the same basic principle: a cavity is alternately exposed to the sun and then concealed while an identical one is kept concealed. Both cavities are heated to the same temperature, so the difference in power consumption corresponds to the total incoming solar energy.

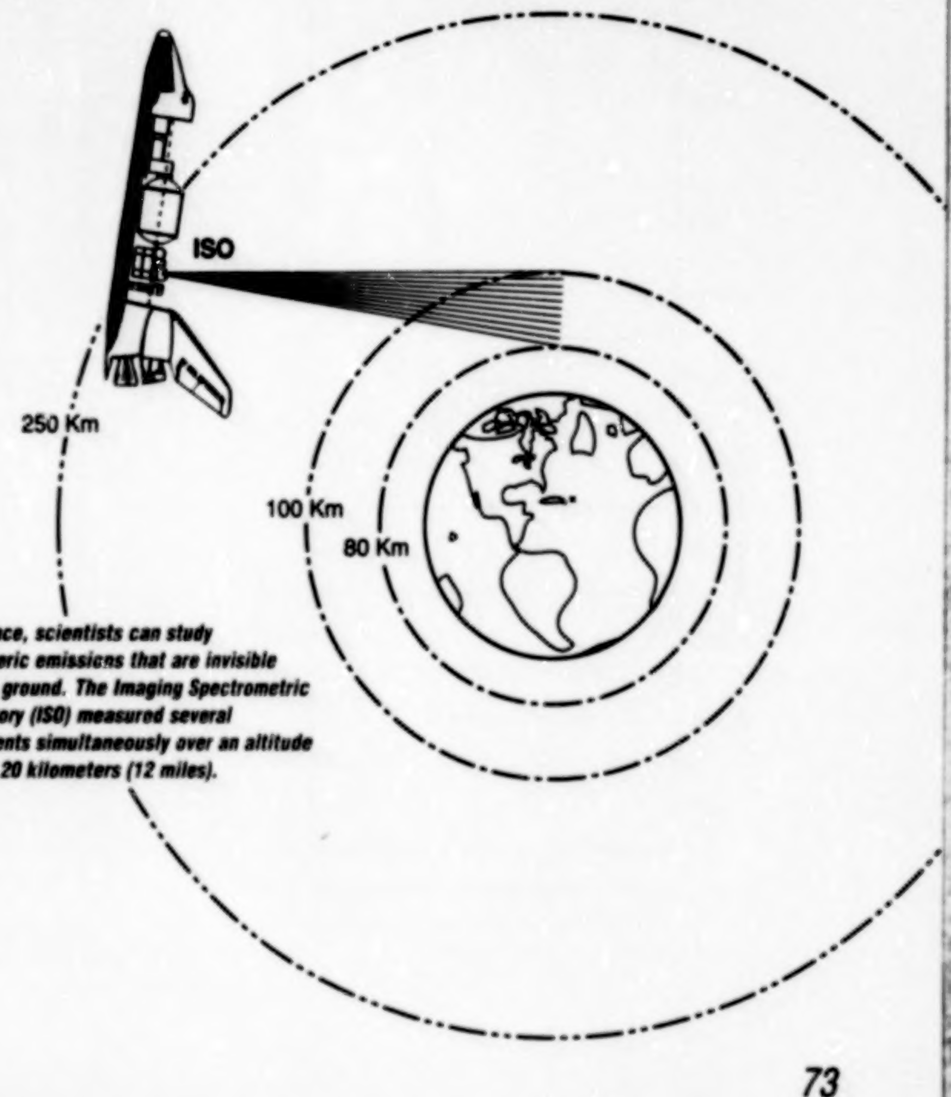
SolCon, one of three radiometers used as a World Radiation Reference, measured the solar output at 1,365 watts per square meter. This concentration is slightly less than all the energy of a 100-watt light bulb falling on a sheet of legal paper. The ACR had some equipment problems that compromised the Spacelab 1 measurements, but a similar unit on the Solar Maximum satellite is operating well. A single set of measurements from either instrument is only a start, as the data necessary for an accurate measurement must be gathered over years and must be compared both with instruments that stay in orbit and with laboratory test data.

It is not enough to know the total energy output of the sun; we must also know how it is distributed across its spectrum of light emissions and how that varies with solar activity. The Solar Spectrum (SolSpec) instrument and the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) measured this distribution. These solar instruments are designed for recalibration in terrestrial laboratories to assure their continued accuracy on reflights.

SolSpec comprises three spectrometers to cover the spectrum from 170 nanometers (1,700 Angstroms, far ultraviolet) to 3,200 nanometers (32,000 Angstroms, infrared). Operating at or near its planned accuracy, SolSpec obtained 35 high-quality solar spectra sets. SUSIM measured ultraviolet intensities in the 120 to 400 nanometer (1,200 to 4,000 Angstroms) region, which represents less than 1 percent of the solar output but varies widely and affects the balance of ozone and other chemicals in the stratosphere. It comprises two spectrometers, one for continual measurement and the other for regular calibration. SUSIM recorded spectra at high resolution with great accuracy. The SUSIM and SolSpec data were compared and for the first time two independent instruments have made measurements that agree within a few percent. These spectra together with repetition of these measurements over a solar cycle will answer questions regarding solar variability in the ultraviolet and will help scientists understand what energies are available to drive chemical reactions in the atmosphere.

Chemistry: Three Spacelab instruments – the Imaging Spectrometric Observatory (ISO), the Atmospheric Trace Molecules Spectroscopy (ATMOS), and the Grille Spectrometer – have assayed the makeup of the middle and upper atmosphere by observing how chemical species emit or absorb radiation.

ISO, actually five spectrometers in one facility, covers the spectrum from 30 to 1,270 nanometers (300 to 12,700 Angstroms). Each spectrometer focuses light from a narrow strip of the atmosphere – 20 kilometers (12 miles) – on solid-state detectors through a spectral grating that breaks a band of light into its colors. Pictures of portions of the atmosphere's structure can be generated in specific spectral lines or colors.



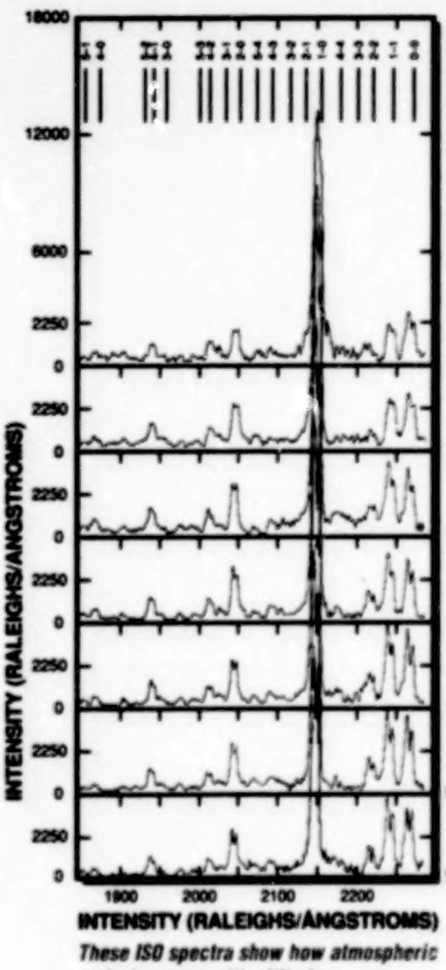
From space, scientists can study atmospheric emissions that are invisible from the ground. The Imaging Spectrometric Observatory (ISO) measured several constituents simultaneously over an altitude range of 20 kilometers (12 miles).

ISO (Spacelab 1) obtained a wealth of information about emissions from the middle atmosphere (or mesosphere) and the thermosphere extending above it. ISO also compiled the first comprehensive spectral atlas of the upper atmosphere, a data base rich in information on several chemical processes. Many unexpected effects were observed that may require years of analysis to be understood. In addition to surveying the natural atmosphere, ISO gathered data on the induced atmosphere around the Shuttle.

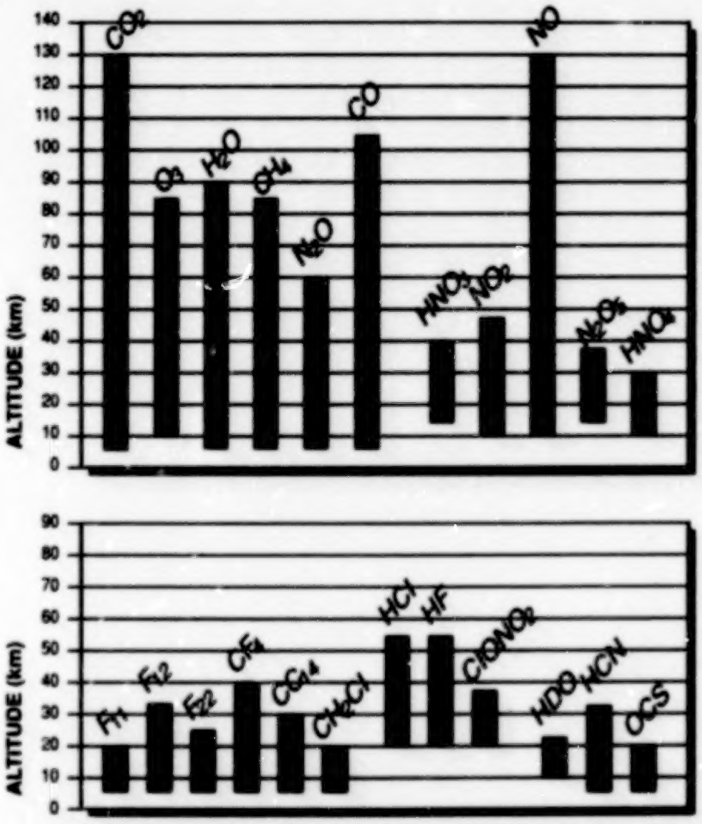
Outstanding simultaneous spatial and spectral images were recorded of several bright emission bands of oxygen, nitrogen, and sodium at around 80 to 100 kilometers (50 to 60 miles) altitude, forming a unique data set for studying the photochemistry of the mesosphere. At higher altitudes, anomalous spectral distributions from molecular nitrogen ions were detected, indicating that photochemical activity may be raising them to high vibrational states. What role this has in atmospheric chemistry is not yet known.

While ISO measures direct light emissions from the atmosphere, ATMOS measures elements illuminated by sunlight. Based on the interferometer principle, ATMOS is designed so that all incoming light except that of the desired wavelength cancels itself out. In 1 second, ATMOS takes 400,000 samples for a single interferogram covering the spectrum from 2,000 to 16,000 nanometers (20,000 to 160,000 Angstroms, near to far infrared). During the Spacelab 3 mission, ATMOS obtained approximately 1,200 atmospheric spectra, each of which contained information on the prime molecular species being studied by investigators. In addition, almost 1,500 full solar spectra were collected and are being used to make a high-resolution solar spectral atlas.

ATMOS extended the altitude ranges over which some 30 molecular species are known. At least five molecules – dinitrogen pentoxide, chlorine nitrate, carbonyl fluoride, methyl chlo-



These ISO spectra show how atmospheric emissions vary with altitude.



This diagram summarizes the vertical range of detection for some of the chemicals observed by Atmospheric Trace Molecules Spectroscopy (ATMOS). The colors denote different groups of atmospheric constituents. The first group is minor gases commonly found in the atmosphere; the rest are trace gases grouped by chemical families. Notable among the results are the detection of trace species that had not been observed previously and the first measurement by remote sensing techniques of the principal natural halocarbon, methylene chloride (CH_2Cl).

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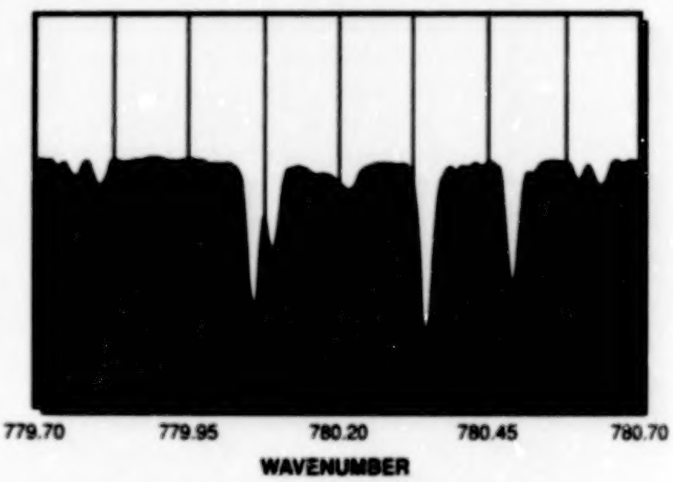
ride, and nitric acid – were found in the stratosphere where their presence only had been suspected. Measurements of other known molecular species in the stratosphere were three to four times more precise than previous data.

The new data show all the nitrogen species at the same time so they can be added to the family of nitrogen-oxygen compounds that figure prominently in much of atmospheric chemistry. Equally important, by not detecting other gases, ATMOS effectively ruled them out as major actors in atmospheric chemistry. Measurements of the mesosphere showed this layer of the atmosphere to be more active than expected, with many minor gases being split by sunlight to start other chemical reactions. The distribution of many compounds, particularly methane and water, and of molecules in the polar atmospheres differed from prediction.

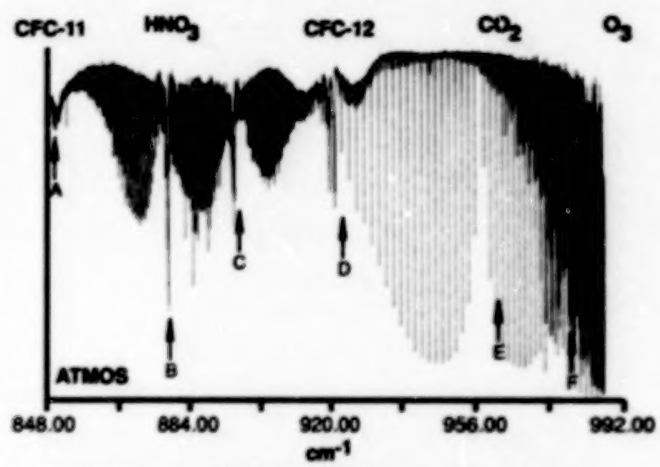
The Grille Spectrometer (Spacelab 1) was designed to observe the atmosphere's constituents from 15 to 150 kilometers (10 to 95 miles) altitude in the 2,500 to 10,000 nanometer (25,000 to 100,000 Angstrom) band. Its name comes from a special grille used as a window for one leg of its optical system and as a mirror for the other to overcome the limitations of many conventional instruments.

The Grille discovered methane in the mesosphere from 50 kilometers (30 miles) up, a higher altitude than previously observed or expected. Methane traces the vertical migration of gases because it comes largely from biological decay and, to a lesser extent, fossil fuel burning. The Grille also observed ozone, water vapor and nitrous oxide in the mesosphere, and carbon monoxide and carbon dioxide in the thermosphere above 85 kilometers (55 miles).

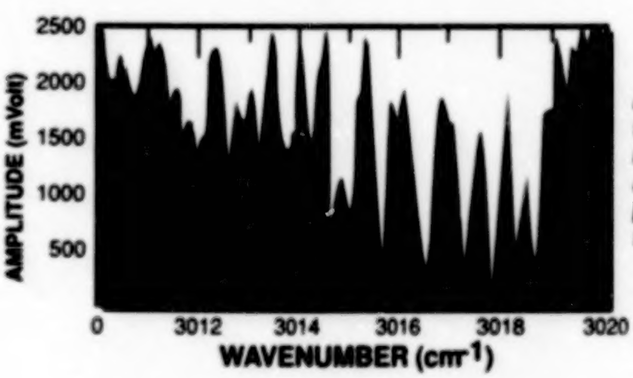
While these instruments were designed to survey the entire makeup of the atmosphere, the Measurement of Air Pollution from Space (MAPS) instrument looked for just one component, carbon monoxide. Its source,



ATMOS confirmed the presence of the trace species ($ClONO_2$) in the stratosphere by acquiring several spectra in large sets. One advantage of Shuttle/Spacelab flights is that several data sets can be acquired and averaged together to accent marginal features that are often overlooked.



This ATMOS figure demonstrates that dramatic atmospheric effects occur throughout the electromagnetic spectrum. The feature marked by A is Freon-11; B and C are two transitions of nitric acid (HNO_3); D is a Freon-12 absorption feature; E is carbon dioxide (CO_2); and beyond F, tightly packed lines of ozone (O_3) dominate the spectrum. (This spectrum does not represent the best resolution of the ATMOS instrument.)



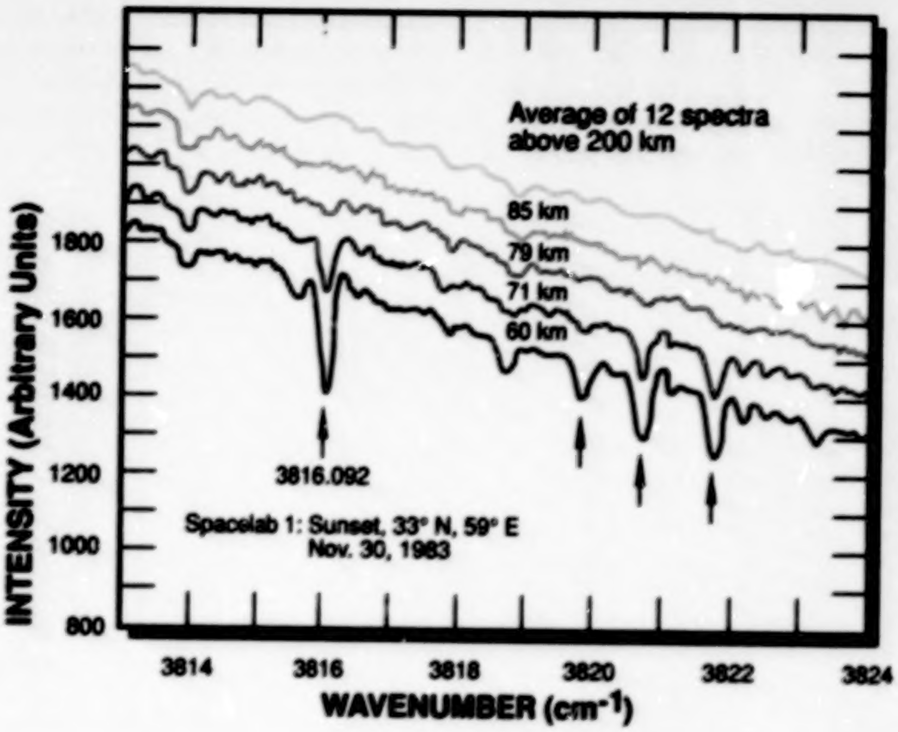
As shown in this spectrum, the Spacelab 1 Grille Spectrometer measured methane in the mesosphere, where it had not been measured before. Since its only atmospheric source is at ground level, methane has been used by atmospheric physicists to model how constituents are transported upward through atmospheric layers.

surprisingly, is largely natural – the decay of organisms. But man's industrial contribution is believed to be approaching nature's output, and "sinks" that absorb carbon monoxide are not well known. Using a small carbon monoxide gas cell to filter out unwanted signals, MAPS measured carbon monoxide at levels of a few parts per billion in the middle and upper atmosphere and as high as 114 parts per billion in the region over central Africa. Data from the second mission look equally precise.

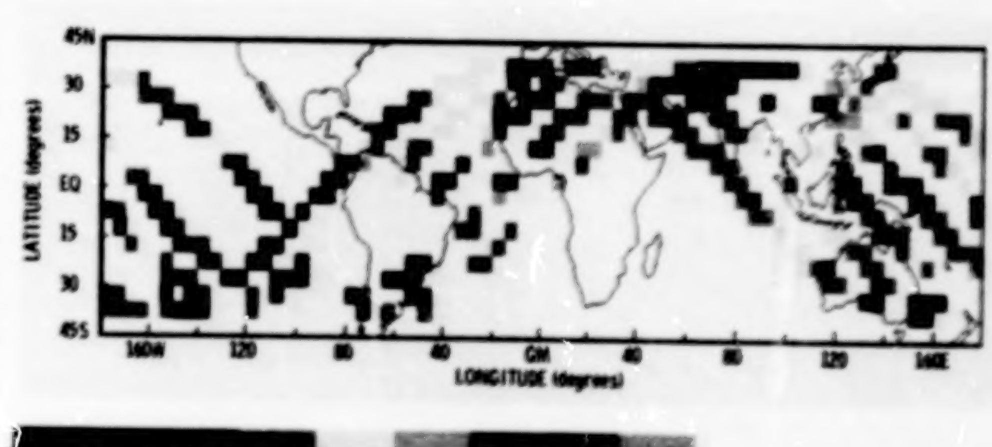
Dynamics: The location of atmospheric chemicals is not static but ever changing in ways not studied by weather satellites. Two Spacelab instruments were designed to observe unique aspects of this motion, and a third modeled stellar and planetary atmospheres.

The upward migration of gases through the atmosphere can be traced with deuterium (heavy hydrogen). The Atmospheric Lyman-Alpha Emissions detector (ALAE, Spacelab 1), in a manner similar to MAPS, used small hydrogen gas cells as filters for the slightly different wavelengths of Lyman-alpha, a "color" emitted by hydrogen and deuterium. ALAE made the first measurements of atomic deuterium in the atmosphere and saw the auroras in the Northern and Southern hemispheres. It also detected the glow of hydrogen atoms and free protons (hydrogen nuclei) colliding and exchanging electrical charges in the corona of hydrogen gas that envelops Earth.

As the sun set, the Grille Spectrometer obtained these spectra of water vapor. The uppermost spectrum is an average of water vapor measured between 200 and 250 kilometers (125 and 155 miles), while the rest of the spectra were obtained at lower altitudes. The arrows indicate the strongest water vapor signatures.



This global chart of the Measurement of Air Pollution from Space data shows carbon monoxide levels measured at a few parts per billion (ppbv) in the middle and upper atmosphere. Measurements as high as 114 ppbv (light pink) were recorded in the region over central Africa.



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In space, scientists can generate more accurate models of atmospheric features such as the great red spot on Jupiter.

The motion of atmospheres on a planetary scale was studied with the Geophysical Fluid Flow Cell (GFFC, Spacelab 3), a simulated planet. Tabletop circulation models of the atmosphere have been used for decades but are limited because, in effect, they have to be flat, which precludes laboratory study of atmospheric dynamics on a full sphere or hemisphere. Only in the microgravity environment of space can scientists generate true three-dimensional experiment models on mathematical scales that exceed ground tests and computer simulations.

The GFFC sandwiched a silicone oil "atmosphere" in a hemispherical capacitor formed by a rotating sapphire dome and a metal sphere. Electrical force fields provided "gravity" and the inner sphere was heated to mimic planetary atmospheres and the solar interior. A 16-mm movie camera with an inverted fisheye lens photographed global flow patterns (as revealed by dyes and schlieren patterns) resulting from fluid density changes.

More than 50,000 images were taken in 103 hours of simulations. Among the expected features were longitudinal "banana" cells like those believed to exist beneath the surface of the sun. What was not expected was that the tips of the banana cells seemed to interact with standing waves encircling the pole. Under different conditions, new phenomena were seen such as spiral waves emanating from the pole; these may be similar to gas flow on Uranus. More discoveries are anticipated as the pictures are analyzed in greater detail.

Microgravity allows scientists to generate true three-dimensional models of atmospheric convection patterns on planets, the sun, and other stars. The image above made in the Geophysical Fluid Flow Cell reveals long "banana" cells that may be similar to convection cells on the sun. As the parameters were changed, a more turbulent convection pattern (below) evolved.

A Global Survey of the Atmosphere: The early Spacelab missions have given atmospheric physicists detailed views of slices of the atmosphere. New species have been detected at various altitudes, and the impacts of natural and human activity are evident; however, the atmosphere changes quickly with effects

rippling from one atmospheric layer to the next. Continuous observation of the entire atmosphere is needed to study with accuracy these dynamic processes as they unfold.

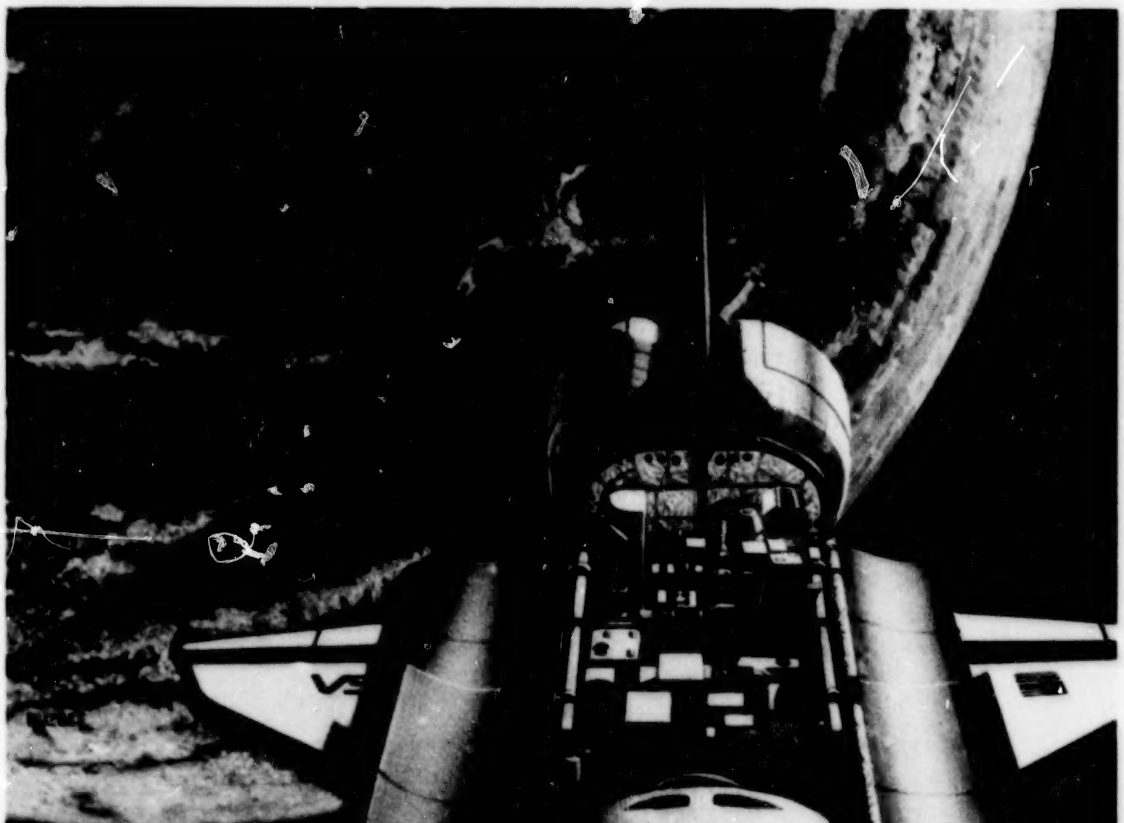
To achieve this goal, instruments will be deployed on platforms that can be controlled from the Space Station or the ground. The Shuttle/Spacelab has carried large and complex instruments into low-Earth orbit; these will be used to design even more sophisticated instruments for platforms.

As on Spacelab missions, instruments attached to the platforms and the Space Station will use remote sensing techniques to detect atmospheric phenomena. Middle and upper atmospheric interactions vary greatly with latitude; therefore, the platforms will be in polar orbits, allowing them to measure the detailed physics of the atmosphere at different latitudes.

Continuous observations will allow atmospheric scientists to study how the atmosphere responds to variations in the solar cycle and to solar stimuli. Campaigns to study the sun-Earth system can be coordinated with solar and plasma physicists working at the Space Station. This teamwork will provide an understanding of the relationship between changes in the sun and the resulting changes in Earth's atmosphere.

Several types of instruments are needed to study the interactive atmosphere. Observatory class instruments will provide a data base for a broad range of investigations from single samples of atmospheric processes to long-term studies of diurnal, seasonal, and solar cyclic responses. Instruments can be programmed to operate at high data rates for collecting sets of measurements on natural events, such as solar flares or the solar wind, as they affect the atmosphere. They also can operate in a "sentry" mode at low data rates to record temperature features and the subtle changes that trigger major events.

Most instruments will be attached to the polar platform operated from the ground, but some can be attached to the Space Station. The Space Station will be important for calibrating sensi-



The Atmospheric Laboratory for Applications and Science (ATLAS) missions aboard the Shuttle will produce an even more precise atlas of atmospheric constituents and more accurate measurements of solar output.

tive instruments. This is especially needed for instruments measuring solar output because they must be very accurate. The Space Station crew will be needed to check out new instruments and repair and refurbish existing ones.

The next step beyond Space Station will be to deploy a platform in a higher orbit; this will enable the atmosphere to be studied simultaneously and continuously. While low-Earth orbit platforms provide greater coverage, it is only by getting higher above Earth that the whole atmosphere can be viewed at once. From higher orbits, scientists will be able to investigate the effects of sudden changes such as magnetic storms or solar flares quickly and globally. It will be possible to make global maps of constituents such as ozone and measure atmospheric features at all latitudes simultaneously.

To add to the catalogue of existing data and prepare for future operations, more flights of the Shuttle/Spacelab are planned. The Atmospheric Laboratory for Applications and Science (ATLAS) will be a comprehensive environmental observatory built around instruments from Spacelabs 1, 2, and 3: the Space Experiments with Particle Accelerators (SEPAC), the Atmospheric Emissions Photometric Imager (AEPI), the Imaging Spectrometric Observatory (ISO), the Atmospheric Trace Molecules Spectroscopy (ATMOS), and the solar constant and solar ultraviolet monitors. New instruments planned for the ATLAS series include a backscatter instrument to measure that portion of the sun's ultraviolet output which is reflected back into space and a scanning microwave radiometer to monitor rainfall locations and intensities from space. This series of missions will measure changes in solar energy output and the distribution of key molecular species in the middle atmosphere. These investigations will reveal new areas of study to be probed as operations are expanded for continuous, global coverage. ■

Atmospheric Science Investigations

OSTA-1/STS-2 *OSTA-3/41-G*	*Measurement of Air Pollution from Space (MAPS)** *H.G. Reichle, NASA Langley Research Center, Hampton, Virginia*
	*Night/Day Optical Survey of Lightning (NOSL)** *B. Vonnegut, State University of New York, Albany, New York*
OSS-1/STS-3 *Spacelab 2/51-F*	*Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)** *G.E. Brueckner, Naval Research Laboratory, Washington, D.C.*
Spacelab 1/STS-9	*Active Cavity Radiometer (ACR)* *R.C. Willson, NASA Jet Propulsion Laboratory, Pasadena, California*
	Grille Spectrometer *M. Ackerman, Space Aeronomy Institute, Brussels, Belgium*
	Imaging Spectrometric Observatory, (ISO) *M.R. Torr, NASA Marshall Space Flight Center, Huntsville, Alabama*
	Investigation of Atmospheric Hydrogen and Deuterium through Measurement of Lyman-Alpha Emission (ALAE) *J.L. Bertaux, National Center for Scientific Research, Paris, France*
	Solar Constant (SolCon) *D. Crommelynck, Royal Meteorological Institute, Brussels, Belgium*
	Solar Spectrum (SolSpec) *G. Thuillier, National Center for Scientific Research, Paris, France*
	Waves in the OH Emissive Layer *M. Hersé, National Center for Scientific Research, Paris, France*
Spacelab 3/51-B	*Atmospheric Trace Molecules Spectroscopy (ATMOS)* *C.B. Farmer, NASA Jet Propulsion Laboratory, Pasadena, California*
	Geophysical Fluid Flow Cell (GFFC) *J.E. Hart, University of Colorado, Boulder, Colorado*

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Chapter 7

Surveying Our Planet: Earth Observations

Blue and green, variable swatches of brown peeking through white clouds, continent after continent – the whole world streams by in a 90-minute Shuttle orbit. From space, our planet looks beautiful but fragile.

Besides aesthetic enjoyment of the view, there are many practical reasons to observe Earth from space. From orbit, it is possible to see both natural and manmade features that are not easily discernible from the ground. This unique perspective is advantageous for mapping, resource monitoring, geology, archaeology, and oceanography.

Maps are basic prerequisites for planning and development, yet despite centuries of exploration about 60 percent of the world has never been mapped in high fidelity, and many existing maps are outdated. Ground-based mapping is tedious and mistakes are easily made; thousands of work-years and millions of dollars would be required to update maps with aerial photography. Satellites such as NASA's Landsat have provided valuable electronic images, but detailed resolution suffers because the satellites are in high orbits and cover large areas. Imaging from the Shuttle, however, may prove to be an effective and economical way to map large areas. The Shuttle's position in low-Earth orbit gives cameras a global view but also allows them to be focused in sharp detail on smaller regions.

At the same time, other hidden treasures may be uncovered. The same techniques used for mapping may reveal locations of minerals or water, artifacts covered from view by sand or vegetation, geological formations, patterns in ocean waves, and glacier movements. Hidden in the jungles, sand dunes, and other undeveloped regions lie untapped resources and historical artifacts. Images from space are being used to uncover some of Earth's secrets.

With a global view from the Shuttle and Spacelab, scientists can focus on geographic details and also see large-scale features that hint of Earth's physical history. The terrestrial land and water masses are part of an interactive, evolving system. Some of the changes are natural processes that have been under way for billions of years; others are the effects of mankind, for we are not mere spectators of nature but active contributors to changes in the environment. Most geological processes occur over grand timescales and are not readily apparent at ground level. From space, however, scientists can see evidence of continental drift, land masses that may once have been connected, and sites that are the birthplaces of volcanos or the burial grounds of ancient rivers. By piecing images together to form a mosaic, they can develop models and perhaps predict future changes, both natural and in response to human activity.

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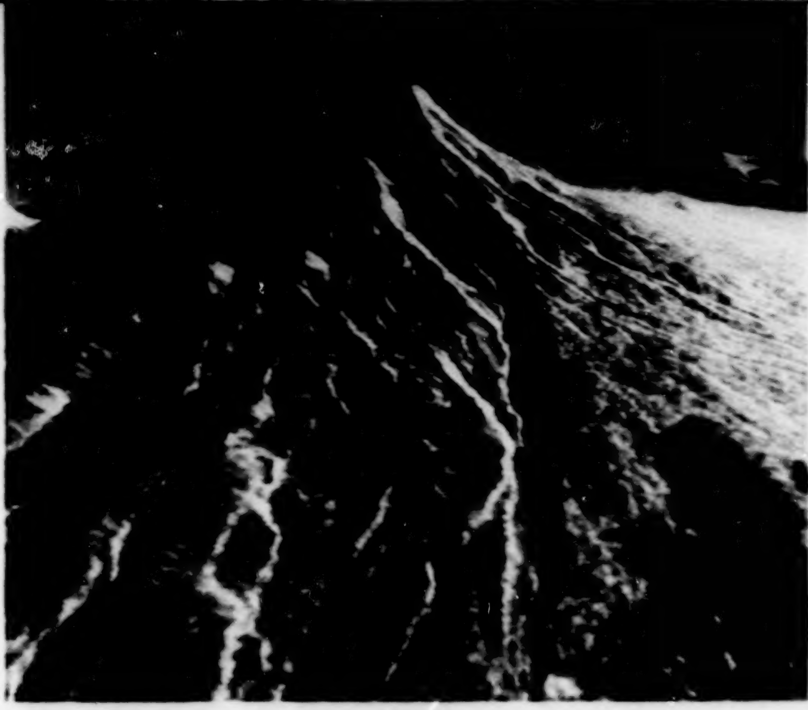
The planetary perspective from space reveals modern changes: depleted mineral and energy resources, cut forests, spills of oil and chemicals into the oceans, networks of roads and canals, and sprawling cities. There is clear evidence that we can alter our habitat significantly within a few human generations.

Aboard the Shuttle, various remote sensing techniques have been used for mapping and other purposes such as the identification of minerals, vegetation studies, acid rain monitoring, geological surveys, and oceanographic investigations. These techniques include photography, radar, and spectroscopy. Often, data obtained by different techniques and instruments are complementary, leading to a better understanding of the feature being observed.

However, it is not enough simply to observe; the information must be used by the international scientific community. Photographs and data from space are returned to Earth, processed, and quickly distributed to investigators around the world. Data from several recent Shuttle missions are already being shared by investigators from every continent. This spirit of cooperation and purpose is essential for understanding and protecting our common homeland, the planet Earth.

Our world can be mapped more quickly and accurately from orbit. A camera carried in the Shuttle payload bay made this photograph which covered 63,366 square kilometers (25,346 square miles) of the eastern Australian coast and the Great Barrier Reef and was used to update maps of the region.



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Radar is another remote sensing technique for surveying our planet. This view of Mount Shasta, California, was generated using two Shuttle Imaging Radar-B (SIR-B) images acquired at different angles. Similar contour modeling experiments were carried out for Africa and South Ameɪica. Using these images, geologists are identifying features such as faults, folds, fractures, dunes, and rock layers.

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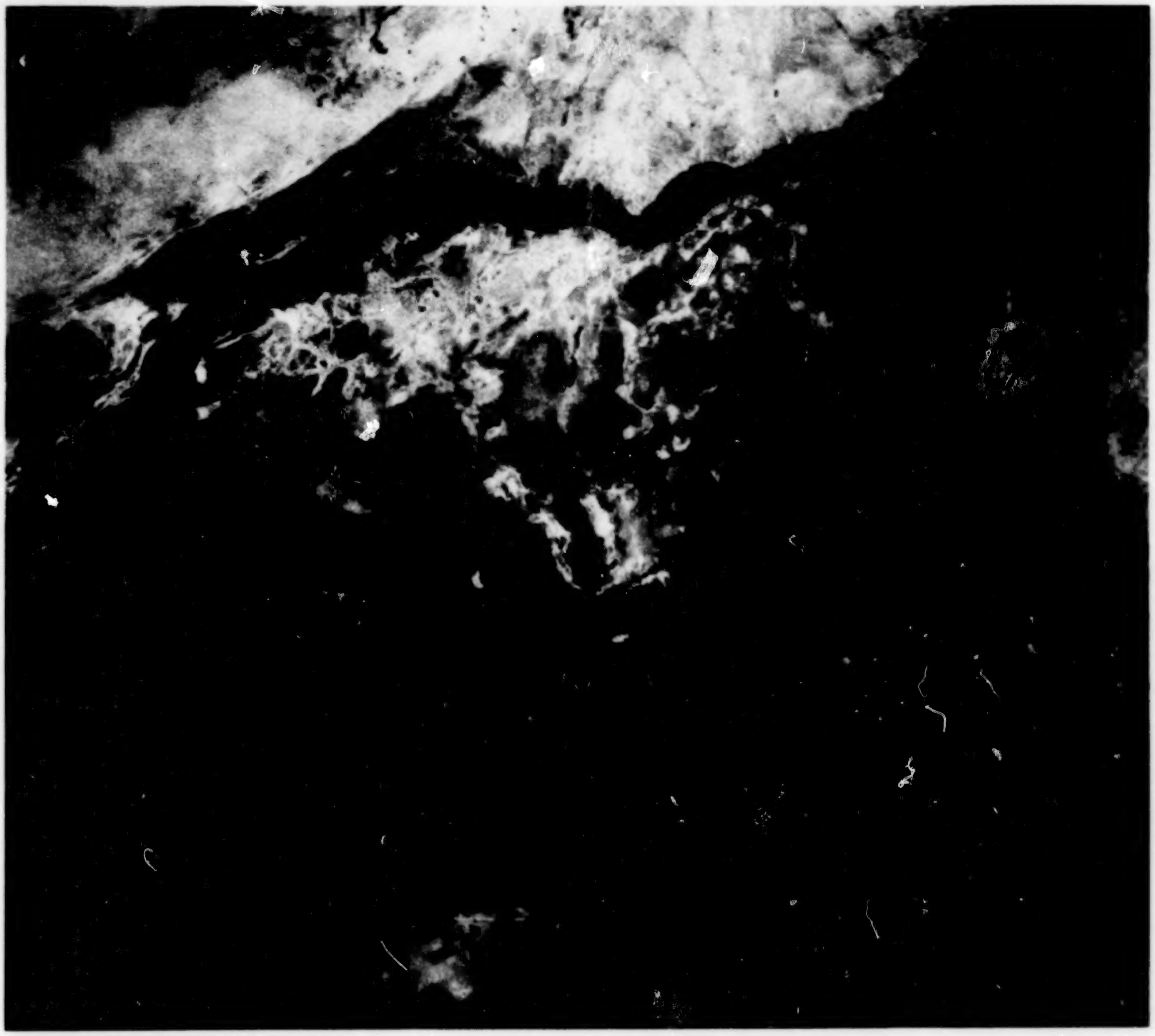
High-Resolution Photography: Two Shuttle instruments, the Metric Camera and the Large Format Camera, combined techniques and equipment for aerial photography with the global view from space to acquire high-resolution images suitable for mapping. Experts say it would take 10 years to make aerial photographs of the regions surveyed by the Metric Camera during 3 days of the 10-day Spacelab 1 mission. After crewmembers saved the experiment by fixing a film jam, 11 million square kilometers (4.2 million square miles) were photographed during the mission. Each 23-centimeter square (9-inch square) film frame covered an area 190 by 190 kilometers (118 by 118 miles), and resolution was 20 meters (66 feet). Roads with widths of 10 meters or more can be recognized. The images are being used to

In this Metric Camera image of the White and Blue Niles in Sudan, Africa, photographic details as small as 10 meters (33 feet) can be resolved. It is possible to identify irrigation and cultivation structures. Developing countries are using these images to make some of their first resource planning maps.



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produce maps at a scale of 1:100,000.

The Metric Camera, a modified aerial survey mapping camera (the Zeiss RMK-A 30-23), was mounted on the optical quality window in the ceiling of the Spacelab module. Three types of film were used: black-and-white negative, color transparency, and false-color infrared. The infrared film makes it easier to identify details not readily apparent in regular color. Photos were taken with an overlap of 60 to 80 percent so that stereoscopic evaluations of overlapping pairs are possible. This helps investigators determine the correct height and shape of certain features.

Details of agricultural patterns, land use, rivers and waterways, geological formations, historical sites, major highways, and buildings are visible in the images. European countries sponsoring the camera's flight are using the images to update maps, some of which have not been revised since the nineteenth century. For example, mountain heights in the Alps have been measured with greater accuracy using the new images.

The international science community submitted 100 proposals for use of the photographs. With these images, developing countries in Africa, Asia, and Latin America are making some of their first resource planning maps. The camera took unprecedented photographs of one of the most isolated regions of China, the Qinghai Plateau, causing a major revision in knowledge of the area.

These images from space reveal imprints left by past and present cultures. Photographs taken over Mexico are being used for archeological research. Traces of the Great Wall have been identified in images of western China.

Other images record features of geological and agricultural importance. Sand dunes hundreds of kilometers long and 70 meters (230 feet) high

Cartographers were able to see major streets and buildings by enlarging this Metric Camera photograph of Munich, Germany.

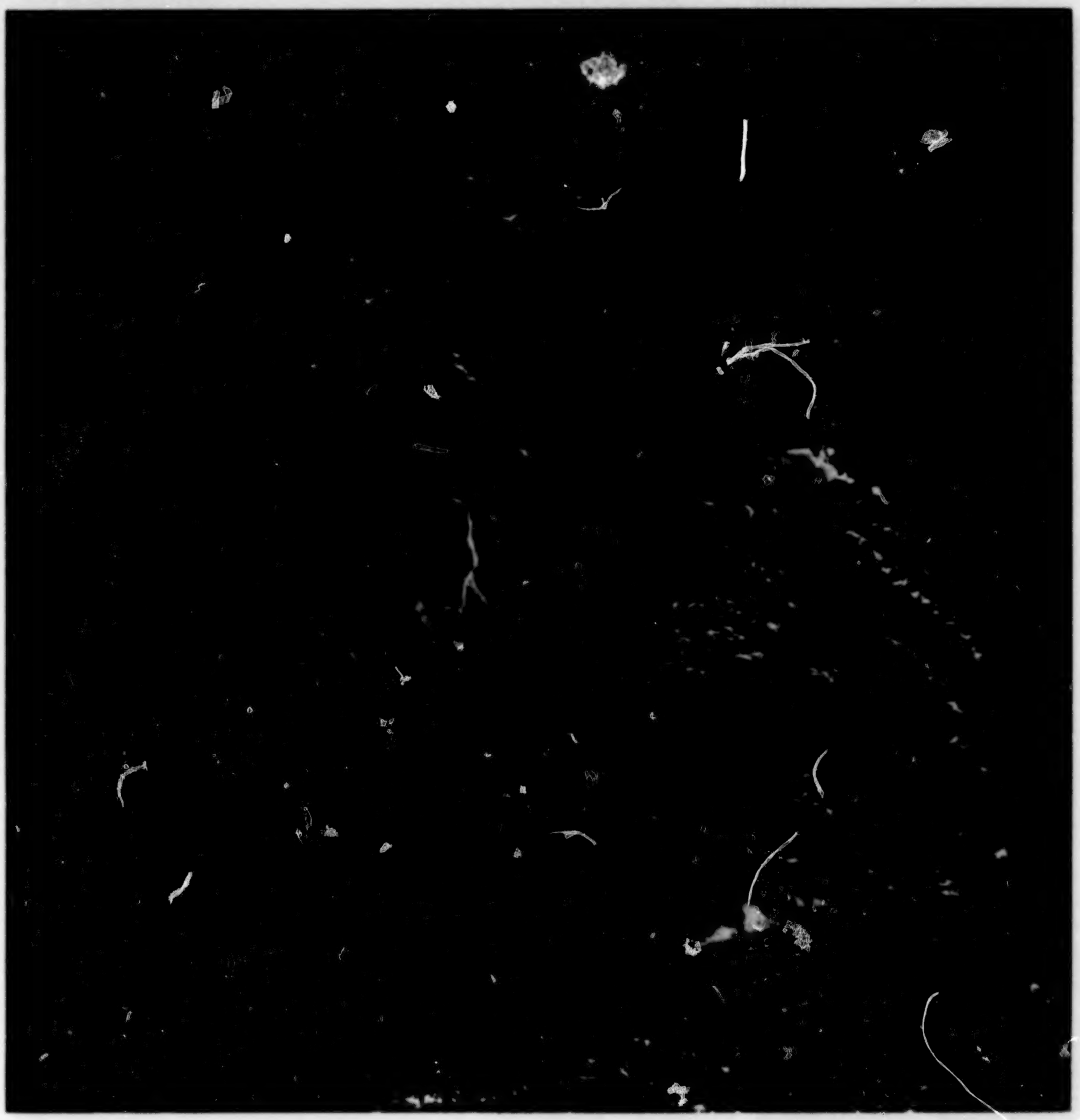
The Strait of Hormuz (Iran) shows recent geological developments in the form of salt dunes, coastal terraces, and uplifted reefs.

were photographed in one of the least known regions of the Sahara Desert. Photographs of the Strait of Gibraltar show the geological and morphological evidence of a former land connection between Africa and Europe. Irrigation and cultivation structures on farms in the Nile River Valley can be identified clearly.

The Large Format Camera flown on the OSTA-3 mission operated similarly to the Metric Camera but was four times bigger and was mounted outside on a Spacelab pallet. The camera produced photographs that were 22.9 by 45.7 centimeters (9 by 18 inches), covering an area of approximately 180 by 362 kilometers (112 by 225 miles). This camera also took one photo after another with 20 to 80 percent overlap so that the images could be compared.

The average spatial resolution of the photographs was 10 to 15 meters (32 to 50 feet), good enough to produce

The Metric Camera can photograph sparsely populated, isolated regions, such as the Horn of Africa.



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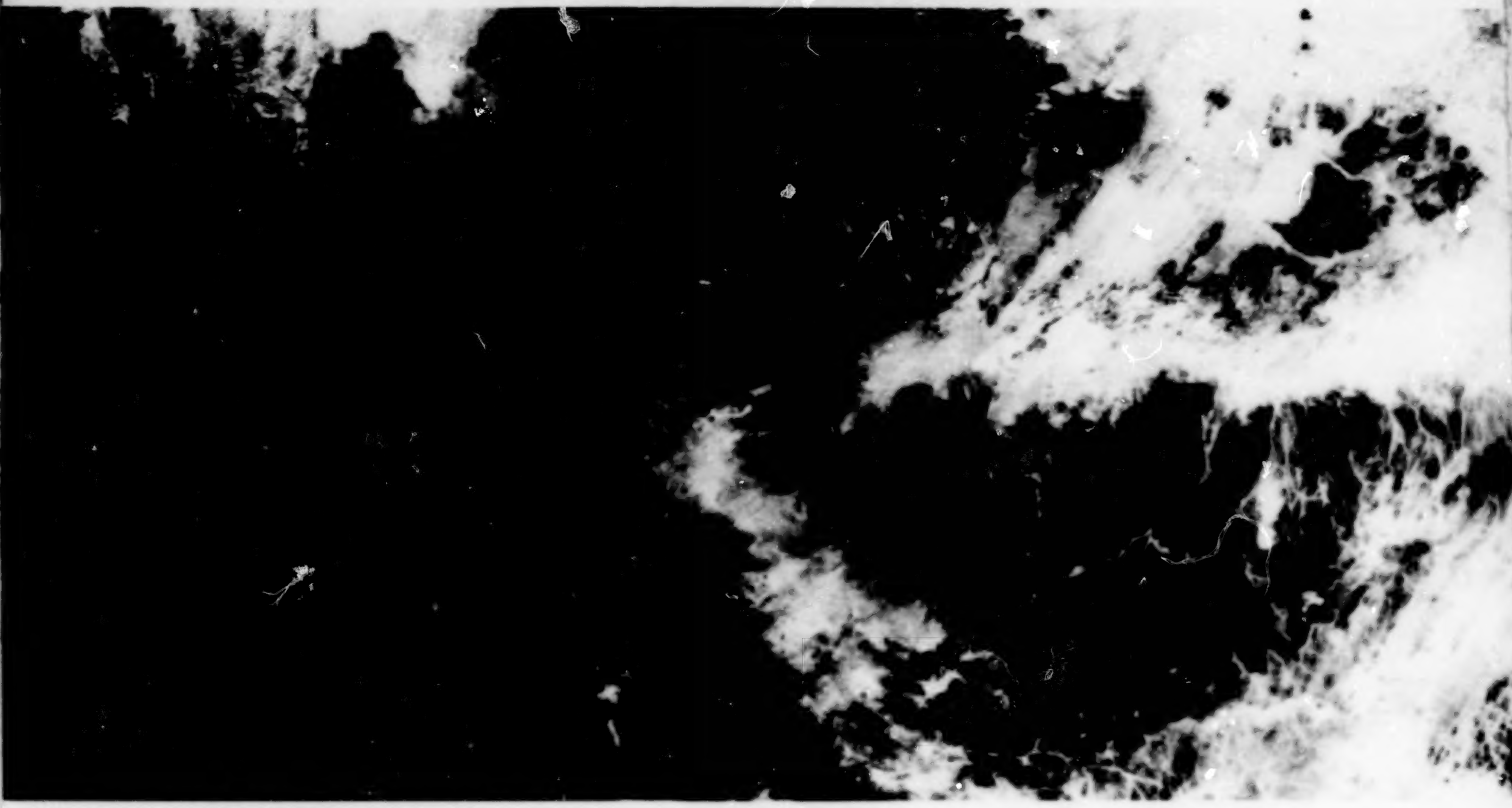
maps at scales of 1:50,000. The resolution is slightly better than the Metric Camera's because a state-of-the-art lens, higher resolution film, and a motion compensation system were used and because the camera was exposed directly to space instead of taking photographs through a window. The resolution was good enough to detect buildings, houses, and streets but not automobiles. In one image, contrails left by planes traveling between New York and Europe can be seen.

Some 2,300 exposures were made during 73 Earth viewing passes. As with the Metric Camera, black-and-white negatives, color transparencies, and color infrared film were used. Some new high-resolution films were tested and proved to be very effective.

The mission was supported by 245 investigators who analyzed data for use in various fields; most of them were from agencies other than NASA

Roads and major buildings are readily evident in this enlarged Large Format Camera image of Mobile, Alabama.



Fossil fuel deposits have been located in the Middle East using Large Format Camera images. This image covers 153,030 square kilometers (59,865 square miles) in Turkey, Lebanon, Israel, Syria, Jordan, Saudi Arabia, and Iraq.

including the National Oceanic and Atmospheric Administration, the Departments of Energy and Defense, the Corps of Engineers, and the U.S. Geological Survey. Teams worked at 500 field sites during the mission, collecting on-site data to confirm or complement photographic information.

High-resolution photographs were taken in the United States, and buildings, streets, and land use patterns were clearly visible. Land types around the world were photographed, including the highest point – Mount Everest in the Himalayas (29,000 feet above sea level) – and one of the lowest – the Dead Sea area in the Holy Land (1,300 feet below sea level). The structure of the Great Barrier Reef could be discerned from photographs of the East Coast of Australia; these and other images are being used to update Australian maps.

The Large Format Camera images are being used for a variety of other projects. Updated topography maps are being made of a national forest in Maine, and land surveys are being made of Wyoming and South Dakota. Fossil fuel deposits have been located in the Middle East, and possible water sources have been identified in Southern Egypt and Ethiopia. By enlarging the images, scientists also may have found some previously undetected impact craters. The images revealed the first proof that blocks of land in China are being forced into the Pacific Ocean along the Kunlan fault; geologists have sent two expeditions to China to investigate the evidence in the images.

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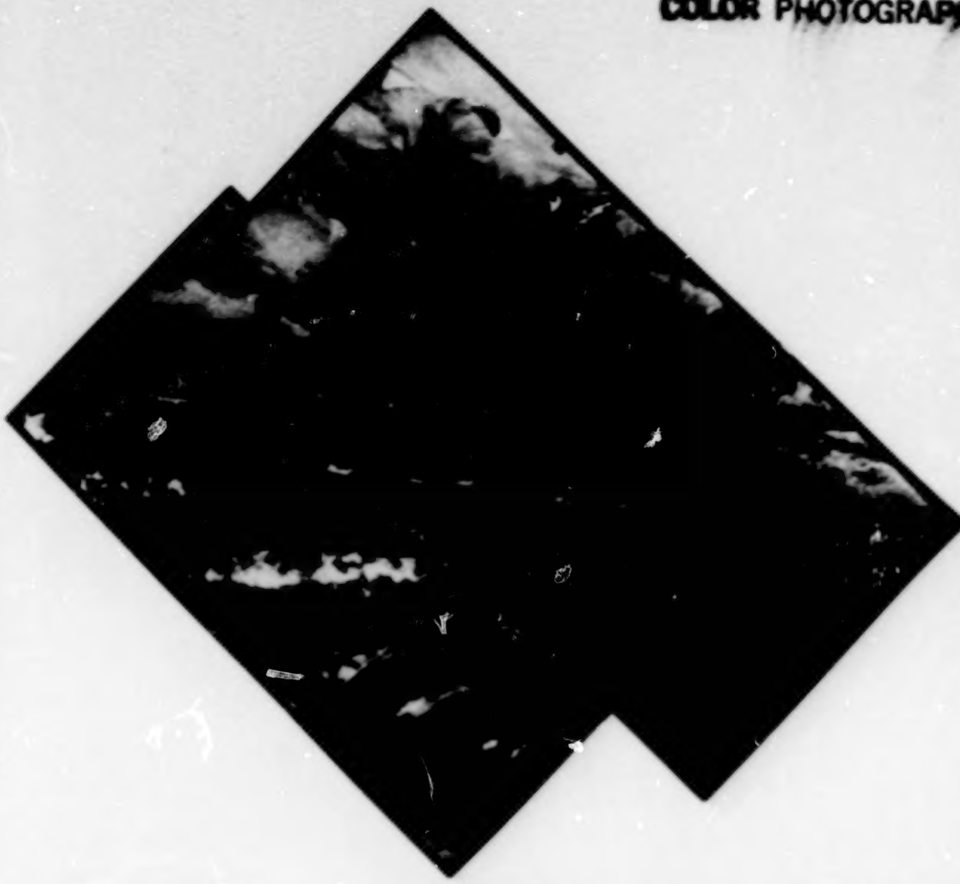
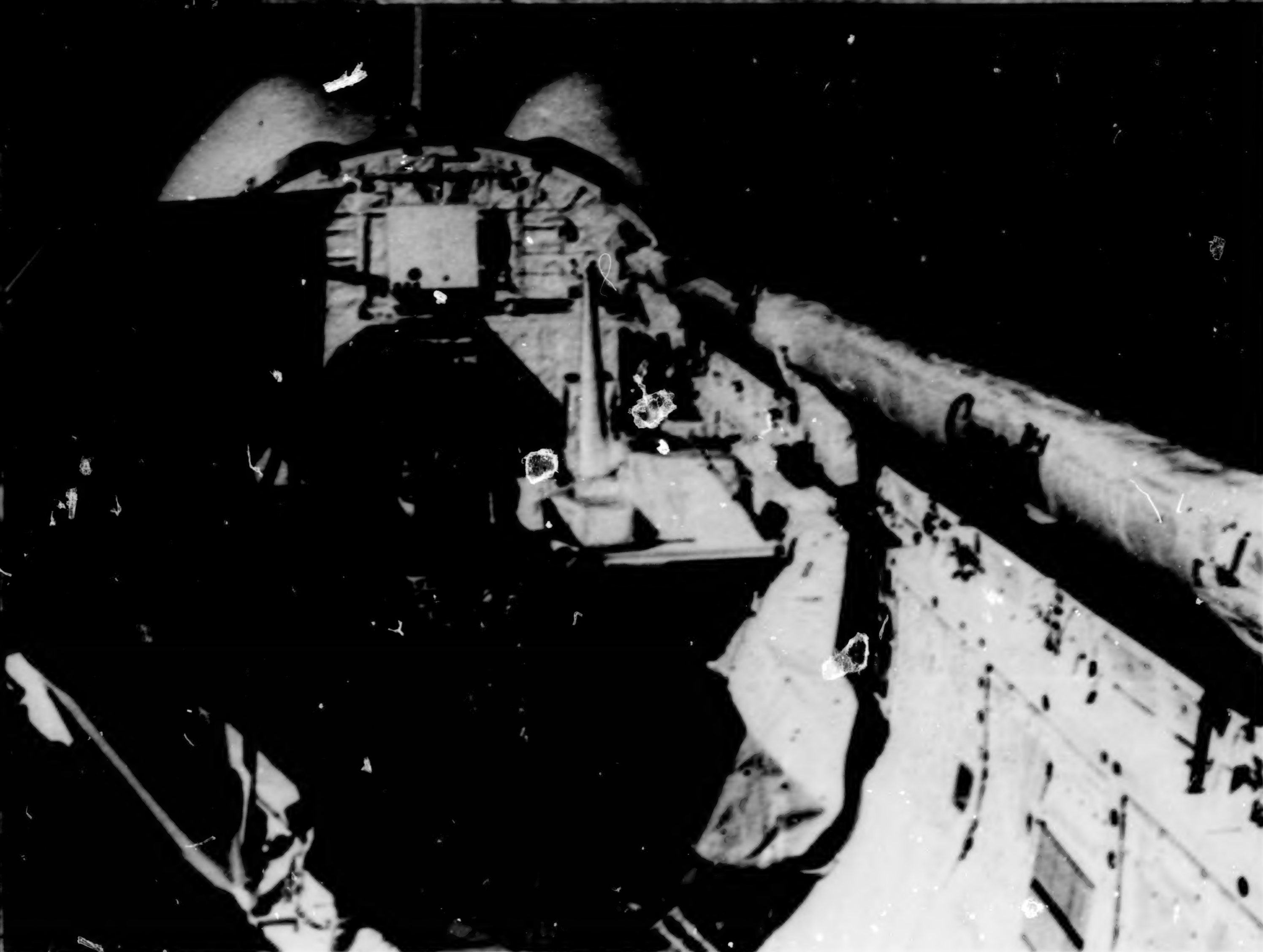


Left: The continuing collision between the Indian subcontinent and Asia has resulted in the formation of the Tibetan plateau, the Himalayas, and major faults. Until high-resolution Large Format Camera images were obtained, there was no direct geological evidence for movement of the faults. This image, with a resolution better than 10 meters (32.8 feet), reveals a 15-kilometer (9.3-mile) segment of the Kunlun fault north of the Ho Sai Hu Basin; the fault stretches from the left of the image to the upper right corner.

Below: Streams flowing southward from the fault scarp have been offset by 1 kilometer (0.62 miles) where they cross the fault trace. Overall, the fault zone is about 1 to 2 kilometers wide; the scarp formed by the most recent movements is about 100 meters (330 feet) high.



The Shuttle Imaging Radar (SIR) was carried on a pallet (left foreground) in the payload bay.

Imaging Through the Clouds, Vegetation, and Surface: Radar is another useful technique for high-resolution mapping. Unlike photography, radar beams can pierce cloud cover and penetrate dense vegetation covering inaccessible tropical regions. Some interesting discoveries have been made using the Shuttle Imaging Radar (SIR) flown aboard the OSTA-1 and OSTA-3 missions.

As the radar is carried along the flight path of the Shuttle, it functions as a greatly elongated antenna. The antenna radiates pulses of microwave energy which are reflected by target areas. The characteristics of the reflected pulses vary according to the surface texture (morphology) and type. For example, sand will alter the radar signal differently than rock or vegetation. The responses are digitized, recorded, and returned to Earth where they are processed to produce images.

SIR-A, the first flight of the Shuttle Imaging Radar, was very successful, acquiring radar images of approximately 26 million square kilometers (10 million square miles), with a resolution of 40 meters (131 feet). The long microwaves were able to penetrate dry sand dunes in the Sahara Desert and image a vanished river system and valleys buried under the sand. Since the Shuttle radar uncovered the remnants of the river, sites of oases have been discovered, and Stone Age artifacts associated with river deposits suggest that these valleys may have been sites of early human occupation. The dry river beds have been used as indicators of water flow in the area; wells have been drilled and several are producing water.

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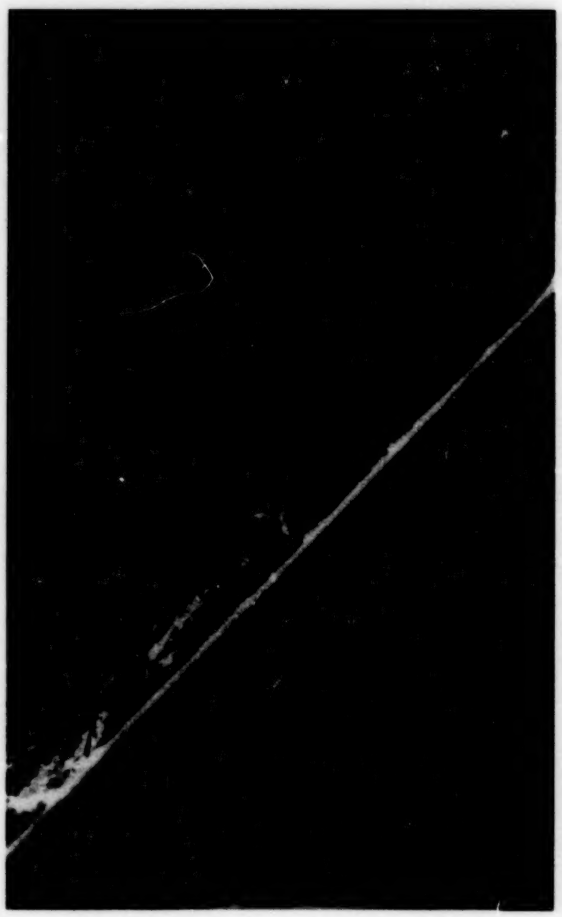
The success of the first flight confirmed that radar could be used from the Shuttle. After its return, the instrument was refurbished, updated to improve its resolution and capabilities, and reflown on a second mission (SIR-B) at a relatively low cost. The resolution of the new radar was 25 meters (82 feet), and the antenna was modified to tilt at angles varying between 15 and 57 degrees. This allowed scientists to gather extra information by "looking" at a target from different angles. This capability permitted viewing a larger area of Earth, since the radar was no longer restricted to the ground directly beneath the Shuttle's orbit. It also allowed large areas to be mapped by varying the look angles so that a mosaic could be made of adjacent areas imaged over several days.

Even though there were some telemetry problems during the OSTA-3 mission, approximately 6 million square miles of Earth were imaged. The drainage channels associated with the vanished river again were revealed. The first sighting also inspired another experiment to see how far the radar could penetrate below the surface of the Earth.

A series of receivers were buried at different depths in a dry lake at Walker Lake, Nevada. During a pass over the site, the deepest receiver, at a depth of 1 meter (3 feet), picked up the radar signals. Soil moisture content also was measured; this type of data could be used for locating water sources and for agricultural monitoring and crop forecasting.



Left: In the Landsat image of a remote part of the desert in Egypt, only surface features of dunes are visible.

Right: SIR-A was able to penetrate beneath the sand to reveal the site of an ancient river bed.

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Investigators also wanted to see how well the radar would penetrate dense areas of vegetation and reveal hidden features, such as breeding grounds for malaria-carrying mosquitos. To do this, they tried to see through the tropical canopies in swamp areas of Bangladesh. The radar images did show areas of still water typical of mosquito habitats.

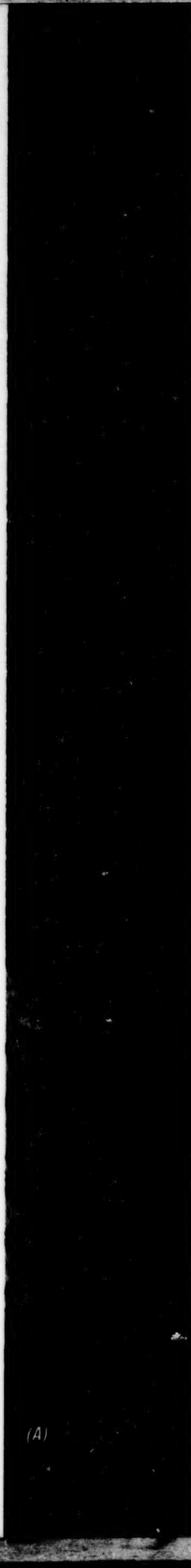
The multi-incidence-angle viewing was used to distinguish surface materials on the basis of their roughness characteristics when imaged at different angles. This enabled investigators to make a three-dimensional model that showed subtle geological details of Mount Shasta, California. Similar contour modeling experiments were carried out in East and South Africa and South America. Structural and geological features such as faults, folds, fractures, dunes, and rock layers are clearly visible.

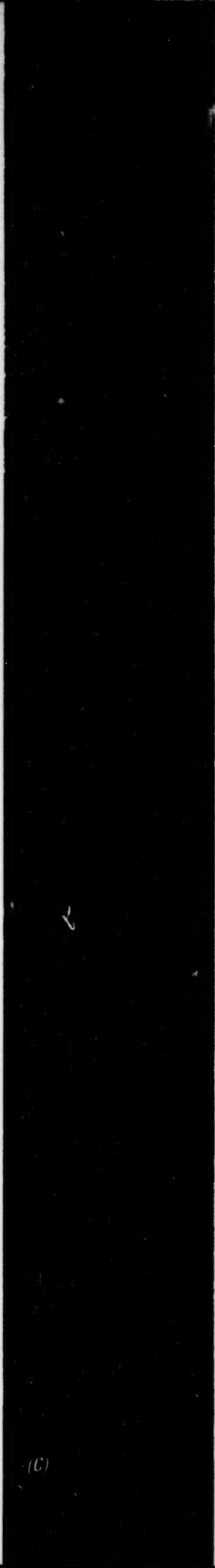
The multiangle viewing was used to classify different types of trees and vegetation by their reflectance properties. (This was possible because different plants reflect radar at amplitudes that vary in pattern as the angle of the radar antenna is changed.) Plant types were successfully identified in Florida and South America.

Other images revealed data about the oceans, natural resources, and geology. Ocean waves of 20 meters (65 feet) or more were measured; polar ice floes were imaged from space; and evidence of oil spills was detected in oceans. The effects of clear-cutting were seen in Germany; tree populations may be monitored from space so that excessive cutting can be avoided. Geological surface boundaries, which may reveal clues to rock types, lava

(A) The Ganges River Delta region of Bangladesh was the site of an experiment to test radar imaging through tropical vegetation. This image was one in a series that proved that soil surfaces and flooded areas under a mangrove canopy can be mapped. Artificial colors in the computer-processed image enhance differences in vegetation and terrain. Pink and yellow represent forested areas, seen most vividly in the coastal forest preserve of Sun:urban on the Indian Ocean. The textured green and pink areas (center) are cultivated fields connected by extensive irrigation and drainage channels. The more uniform rose-hued area (top) is part of the Ganges flood plain subject to flooding during monsoon season.

(B) Artificial colors were used to enhance differences in surface characteristics in this SIR-B image of Hawaii. South Point is the bright red surface (bottom), Kilauea Crater is the circular feature (center), and the two black lines (upper right) are air strips at Hilo Airport. Red areas represent smooth ash cover, dark green is smooth pahoehoe lava, light green is rough lava, and light blue is vegetation cover.





flows inside volcanos, and previously undetected impact craters were imaged.

SIR-B took advantage of an unexpected opportunity to monitor Hurricane Josephine. The instrument detected wave patterns associated with the storm's movement and speed. This type of information would be useful in determining when and how a storm might strike a coast.

During the SIR-B mission, more than 40 co-investigators were dispatched at various field sites around the world. Their observations at places being studied from space helped to confirm that the data obtained are accurate.

(C) This image of northeastern Florida is being used to assess coniferous timber stands and management practices. The artificial colors in this computer-processed image enhance differences in vegetation and terrain. Yellowish green areas are generally stands of cypress drenched in early morning dew. Dark green and purple areas are agricultural fields, and bright orange regions denote drainage channels. The Gulf of Mexico is at the bottom.

(D) The Rhine River, the Black Forest, and West Germany appear in this SIR-B investigation of the utility of radar imagery for classifying crops and monitoring the health of timber stands. The bright spots in the images are urban areas where buildings strongly reflect the radar signal. Freiberg is the largest bright spot in the image. The Black Forest is just above Freiberg. Mottled dark spots represent clear-cut areas in the forest, which appears as a uniform gray (left). The small bright circle (lower right) is the octagonal walled city of Neuf Brisach in France.

Locating Minerals and Studying the Oceans: Although photography and radar are able to reveal surface geological features, they are not useful for identifying specific minerals. The Shuttle Multispectral Infrared Radiometer demonstrated that this can be done by another technique – spectroscopy. Minerals on Earth reflect light at specific wavelengths or spectral lines that can be identified with a spectrometer.

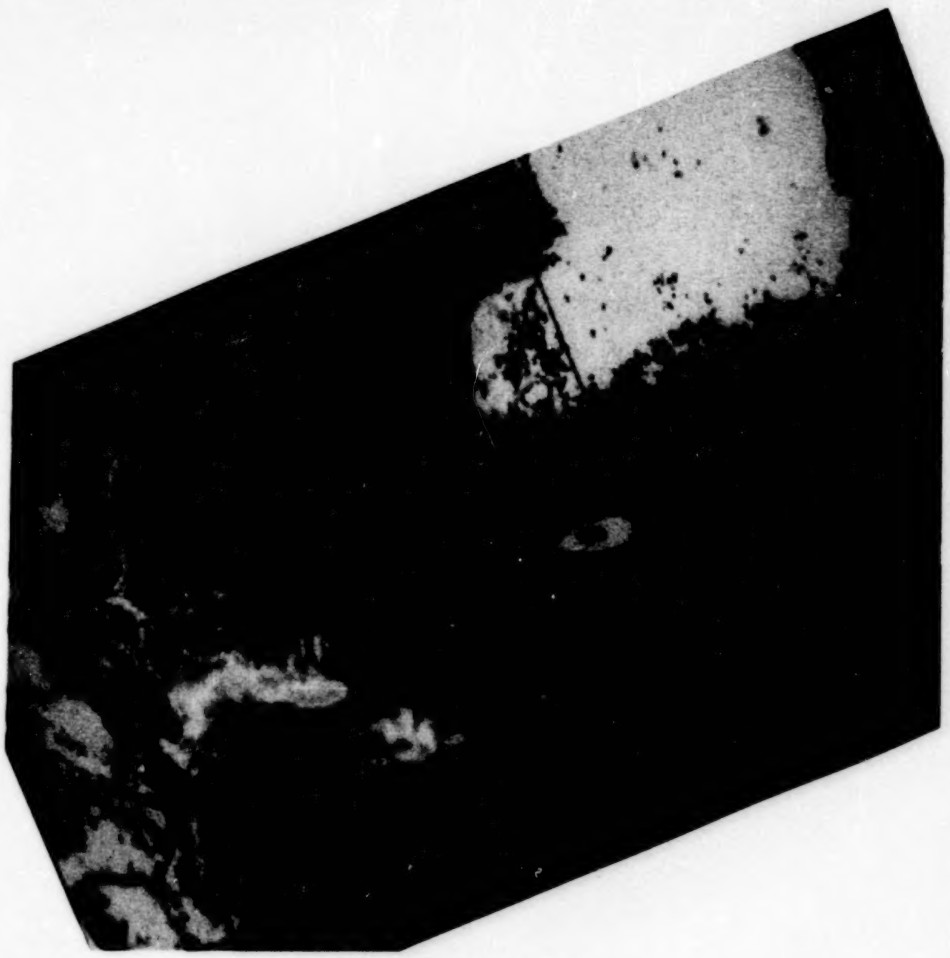
This experiment was inspired by the use of Landsat data to identify limonite, a major iron ore. The Landsat satellite has four broad spectral channels at short wavelengths, but because many minerals reflect at longer wavelengths, they might be seen by a differently tuned instrument. The Shuttle Multispectral Infrared Radiometer records spectra in 10 channels between 0.5 and 2.4 microns at a spatial resolution of 100 meters (328 feet). In particular, investigators are interested in identifying carbonate and hydroxl-bearing minerals, such as clays, which radiate brightly in the 2.0 to 2.4 micron spectral range.

As the instrument makes measurements, the ground track is photographed by a 16-mm camera so that mineral spectra can be matched with locations. During the second Shuttle flight, 400,000 spectra were obtained over the eastern United States, Mexico, southern Europe, North Africa, the Middle East, and China.

In the laboratory before the flight, the instrument was calibrated by obtaining spectra of pure minerals. For verification, the spectral data taken in orbit were compared with laboratory spectra and with the spectra of minerals collected at the observation sites. The next steps in the evolution of this instrument are to increase spectral resolution for enhanced ability to identify specific minerals and to eliminate spectral absorption by vegetation which confounds the mineral spectra.

Interesting mineral signatures were identified in the Baja region of Mexico. A large hydrothermally altered area was identified in Mexico for the first time; the rock in this area is associated with many types of ore deposits and contains minerals having intense, distinctive spectral signatures. The minerals identified were clays (pryophyllite, dickite, diaspore, kaolinine, and K-mica) along with molybdenum, boron, tin, zirconium, and silver. Field trips to the area after the mission confirmed that this was a thermally altered terrain containing many of the minerals identified by space spectroscopy.

The ocean also reveals its biological contents and circulation patterns by the reflectance properties of its various components. The OSTA-1 Ocean Color Experiment employed an eight-channel multispectral imaging sensor to measure solar radiation reflected from ocean surfaces at wavelengths of 0.4 to 0.8 microns. The instrument was designed to detect variations in the pigmentation of ocean surface waters. The color varies in relationship to the presence of chlorophyll in phytoplankton algae.



This false-color image of the Yellow Sea made for the Ocean Color Experiment shows chlorophyll pigments (green and yellow) indicating the presence of phytoplankton.

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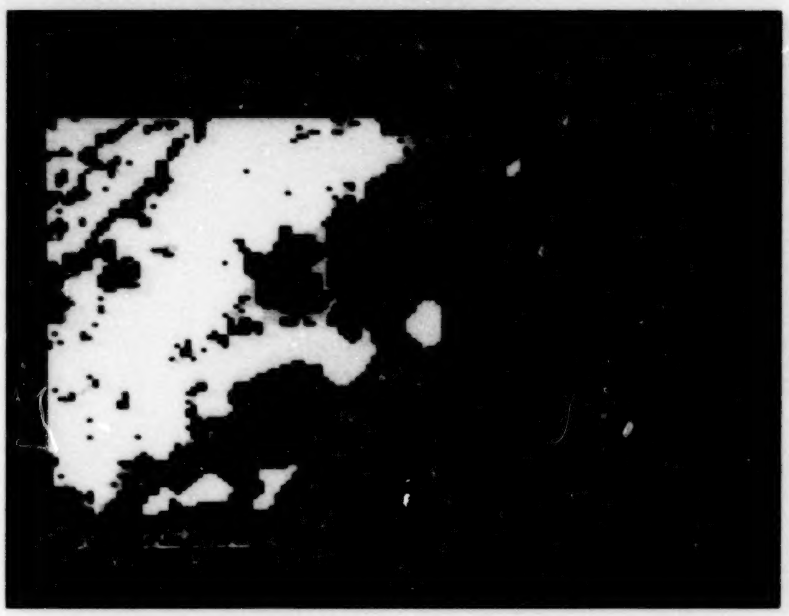
The ocean images were digitized and enhanced by computer to emphasize patterns of chlorophyll distribution and, in one case, to show bottom topography. The chlorophyll pattern in the Yellow Sea between China and Korea was evident in one scene, and the effects of the discharge of rivers into the sea were observed.

As patches of plankton were carried in the ocean currents, reflectivity changes were observed over the Strait of Gibraltar during successive Shuttle passes. These were used to estimate the direction and velocity of surface currents near the entrance to the Mediterranean.

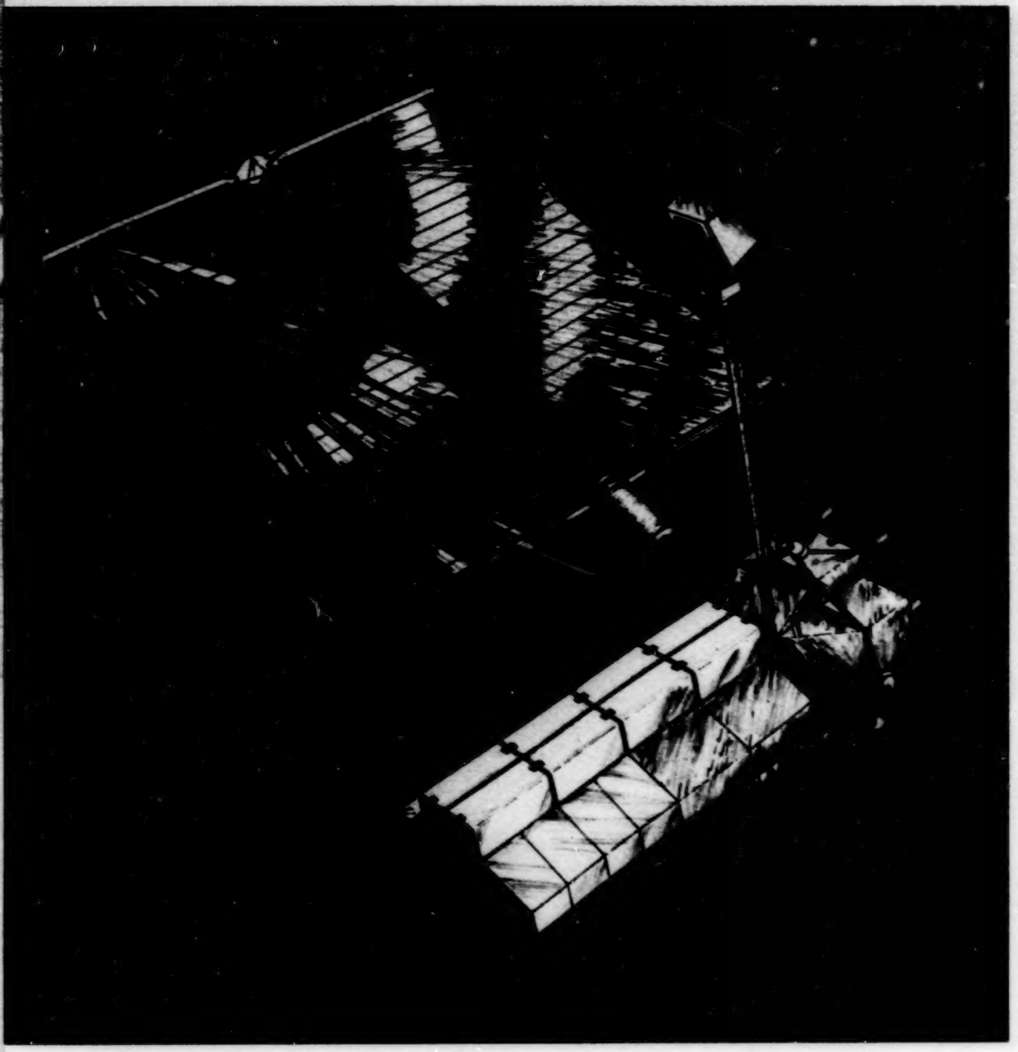
The variability in water depth over the Grand Bahama Bank was estimated using the blue-green channel of the instrument. The area is characterized by its scarcity of planktonic marine life, and the blue-green components of visible light that are usually absorbed by chlorophyll penetrated the water and were reflected from the bottom. Using the return signal, investigators estimated water depths ranging from a few meters to tens of meters.

The Ocean Color Experiment demonstrated the feasibility of mapping chlorophyll concentration in the open ocean. This capability could be used to monitor global changes in phytoplankton abundances from space. Phytoplankton are a key building block at the base of Earth's food chain, and information on their distribution and total abundance could be important to long-term studies of global ecology.

Refining Observation Techniques: The Shuttle missions also have given scientists an opportunity to refine Earth observation techniques. For example, stereoscopic viewing has been accomplished using both photography and radar images. This results in greater accuracies when measuring heights and distances.



The digitized image (bottom) was made for the Feature Identification and Location Experiment (FILE) and compared to the ground truth image (top). The FILE system denotes clouds as white, ocean as blue, and land as green. Similar systems may be placed on satellites so that valuable viewing time is not wasted on cloudy areas.



As part of NASA's Earth Observation System (EOS) program, a polar orbiting platform will allow instruments to view the entire Earth 15 times a day.

The Feature Identification and Location Experiment (FILE, OSTA-1 and OSTA-3) tested a system that will help satellites identify good viewing conditions. The idea is to save precious viewing time by preventing remote sensing satellites from gathering unusable data during cloud cover. The instrument uses wavelengths to classify surface features into four categories: (1) vegetation, (2) bare ground, (3) water, and (4) clouds, snow, and ice.

Essential parts of the instrument are two television cameras, each consisting of an array of charge-coupled detectors. One camera senses reflected radiation at the 0.65-micron wavelength (visible red), and the other senses radiation at 0.85 microns (near infrared). The ratio of the two signals can be used to categorize the scene as either mostly clouds or mostly another feature. Images from the two cameras are digitized and color-coded according to category. OSTA images show that the ratio correctly identified the various features.

Continuous Global Observations: As we study Earth from space, national boundaries become less distinct. With the Shuttle, scientists around the world have taken the first step to study Earth as an integrated system. It is only through continued international cooperation in planning and carrying out investigations that our planet can be studied on a global scale. This effort requires a coordinated program of long-term, systematic observations. The new technology tested aboard the Space Shuttle can be attached to platforms and the Space Station for continuous viewing and longer stays in space. To understand and verify these observations, worldwide ground and airborne observations will continue to be critical.

In the Space Station era, Earth observations will meet the needs of a broad and diverse community of scien-

tists. Some scientists need close-up views of local areas, others need a view of the Earth's entire surface, and still others need to view the atmosphere. To meet these requirements, an Earth Observation System (EOS) is being developed.

Instruments will be placed on platforms that orbit Earth's poles at inclinations higher than the Space Station where they have a more global view of our planet. Sophisticated instruments on polar platforms will increase the types of observations possible; scientists will be able to focus instruments on almost any point on the Earth instantaneously, view with less cloud interference, select observing times, survey small-scale, rapidly changing events, and monitor events under various cyclic conditions.

Other instruments may be attached to the Space Station, which is at a lower altitude and inclination and offers better close-up views of tropical forests and other areas. The Space Station also will be essential for assembling, testing, and deploying instruments to higher orbits as well as for servicing, repairing, and upgrading instruments.

The EOS will be coupled to advanced information systems to ensure that data are collected, distributed, analyzed, and archived for use by the science community. In the meantime, the Shuttle/Spacelab must still be used to develop the instruments and test the technologies for Earth observations. The Shuttle also is valuable as a testbed for information systems and for developing procedures for remotely operated instruments.

The Shuttle will remain in service as a platform for Earth observations. Evolving from the Shuttle Imaging Radar on OSTA-1 and OSTA-3, the Shuttle Imaging Radar-C will gather even more information by using several frequencies and polarizations to map the entire globe. The Large Format Camera may be carried as a complement to provide visible light imagery of the world and to improve global cartography. The ability of the Shuttle Imaging Spectrometer Experiment (SISEX) to provide images of the Earth in 128 spectral bands at once will be tested on the Shuttle before it becomes a part of the next generation of Earth-monitoring satellites.

To solve some of the problems in a modern, rapidly changing world, Earth must be studied as an integrated system. This requires an interdisciplinary approach, with life scientists, atmospheric scientists, geologists, and investigators from many other fields working together. This united effort can only be accomplished in space where we see the Earth as a whole. ■

Earth Observation Investigations

OSTA-1/STS-2	*Feature Identification and Location Experiment (FILE)* *R.T. Schappell, Martin-Marietta, Denver, Colorado*
	Ocean Color Experiment *H.H. Kim, NASA Goddard Space Flight Center, Greenbelt, Maryland*
	Shuttle Imaging Radar (SIR-A) *C. Elachi, NASA Jet Propulsion Laboratory, Pasadena, California*
	Shuttle Multispectral Infrared Radiometer *A. Goetz, University of Colorado, Boulder, Colorado*
Spacelab 1/STS-9	*Metric Camera* *M. Reynolds, European Space Agency, Noordwijk, The Netherlands* *G. Konecny, University of Hannover, Germany*
	Microwave Remote Sensing Experiment *G. Dieterle, European Space Agency, Paris, France*
OSTA-3/41-G	*Feature Identification and Location Experiment (FILE)** *W.E. Sivertson, NASA Langley Research Center, Hampton, Virginia*
	Large Format Camera *B.H. Mollberg, NASA Johnson Space Center, Houston, Texas*
	Shuttle Imaging Radar (SIR-B) *C. Elachi, NASA Jet Propulsion Laboratory, Pasadena, California*

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Chapter 8

Charting the Universe: Astronomy and Astrophysics

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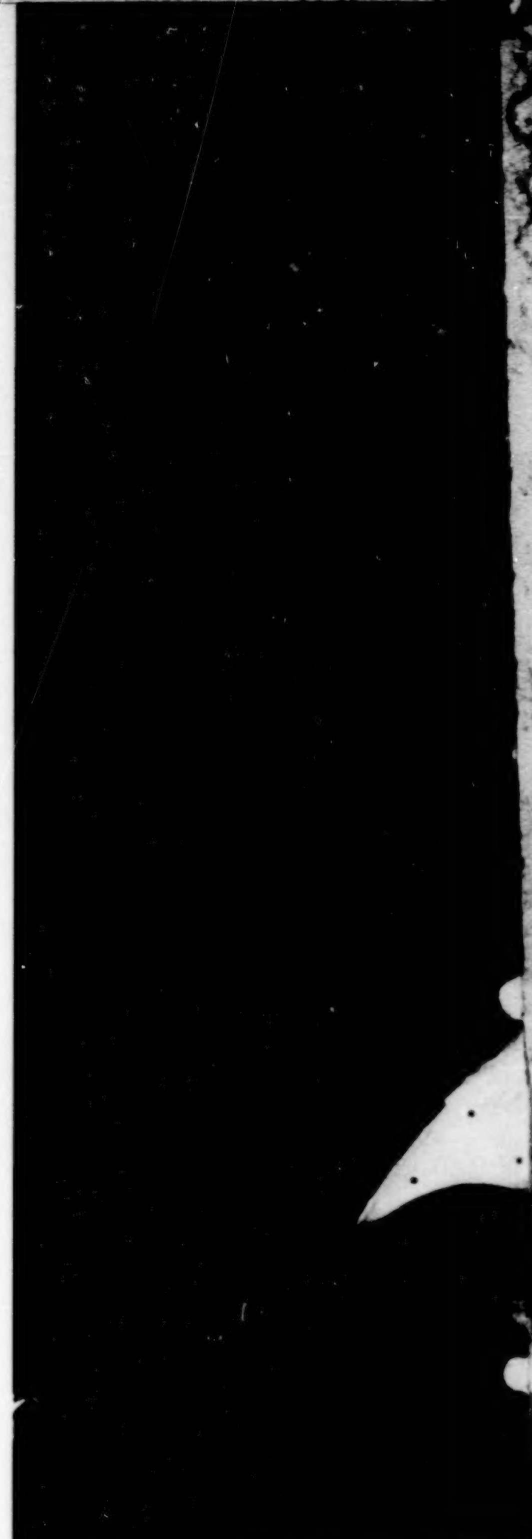


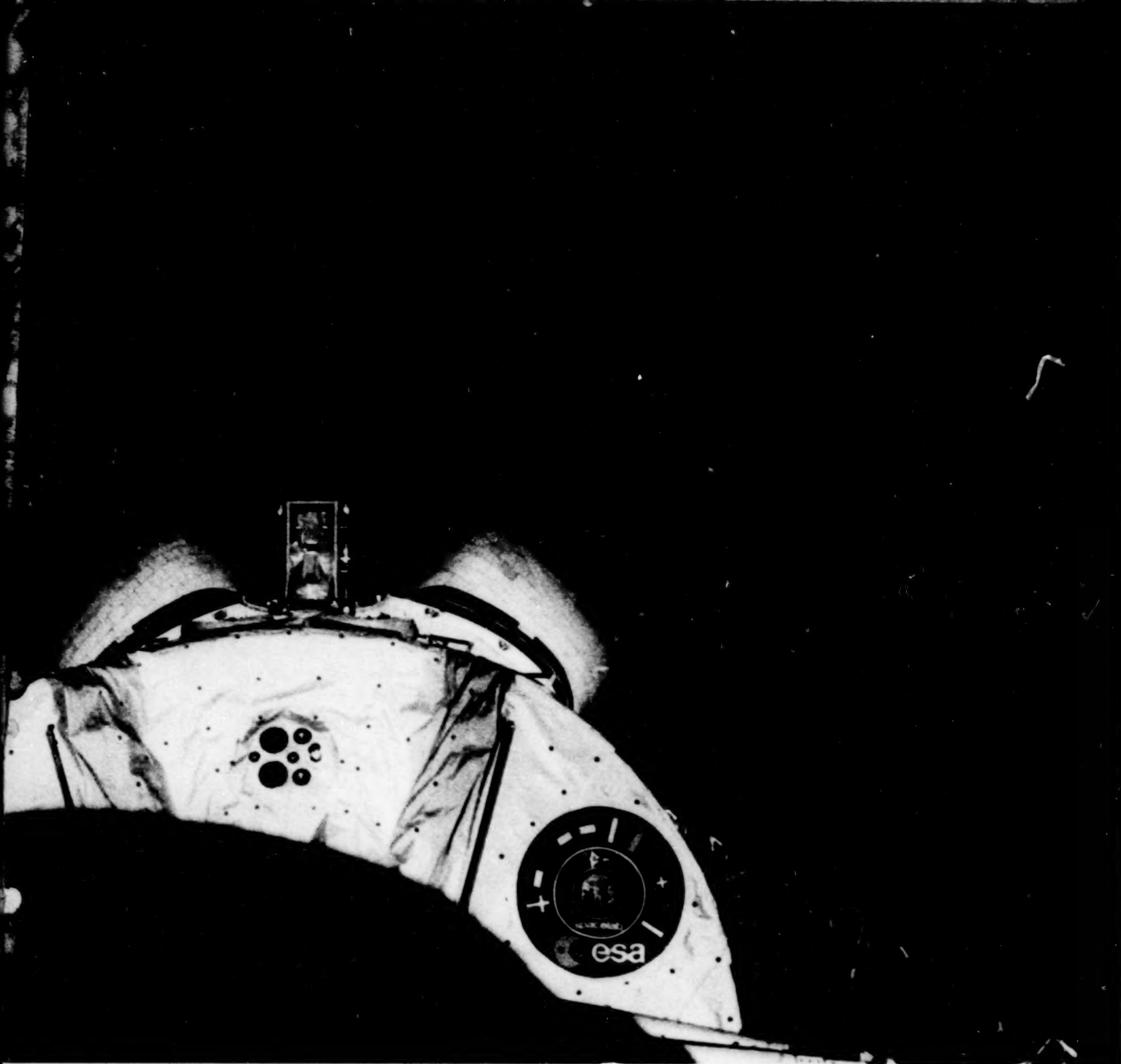
Astronomical observatories on Earth, even those on the highest mountain peaks, are plagued by clouds and poor visibility and by the fact that most radiation from celestial objects never penetrates the atmosphere. Thus, much information about the universe cannot be obtained from the ground, and what is available is seriously degraded by atmospheric conditions. Above the atmosphere, however, the view improves dramatically; if it were practical, most telescopes would be used in space.

For almost three decades, astronomers have put telescopes and other instruments into space to take advantage of the superior viewing conditions there. Observations from rockets and satellites have opened windows to a wondrous universe seen in wavelengths other than visible light. Infrared observations expose regions of star formation, while ultraviolet radiation and X-rays reveal high-energy events such as the explosive death of stars. Cosmic ray detectors record the arrival and travel paths of these high-speed nuclei from beyond our solar system.

Spacelab and the Shuttle have enabled scientists to place larger and more powerful instruments above the atmosphere, to operate them directly as if they were in an observatory on the ground, and to return film and instruments for postflight analysis. Future Shuttle flights also will provide opportunities for co-observation, viewing the same object or area with different instruments simultaneously; for example, stars may be observed by ultraviolet and X-ray telescopes at the same time for a correlated record of their behavior.

The results are high-resolution images and measurements across the electromagnetic spectrum, target selection and fine control of observations by onboard experts or scientists on the

For the Spacelab 2 mission, three large astronomical instruments – an X-ray telescope, an infrared telescope, and a cosmic ray detector (front to back) – were carried in the Shuttle payload bay.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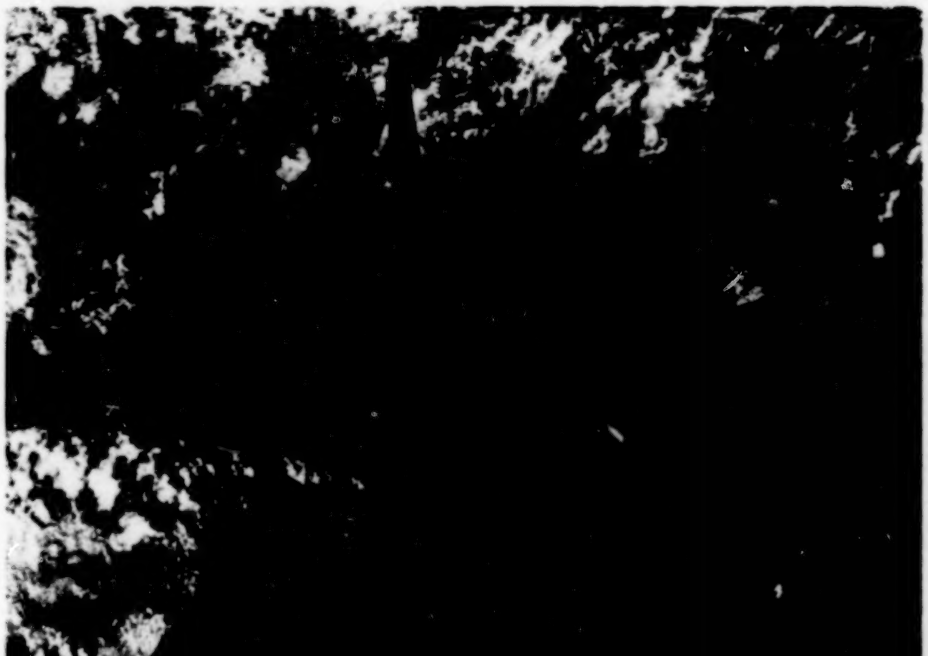
By analyzing the tracks of ions in a detector, scientists can determine the charge and identity of cosmic rays.



During the Spacelab 2 mission, an X-ray telescope obtained the highest energy X-ray maps of celestial objects made to date.

ground, and new data that cannot be collected by less sensitive instruments. Instruments in space can map the sky with great accuracy, take wide-angle photographs or zero in on single objects, record very faint radiation from sources within our galaxy or far beyond, capture cosmic ray particles traveling at nearly the speed of light, measure how much radiation is emitted from a source at a given wavelength and how it changes, and peer into events and processes that are invisible from the ground.

While the Shuttle is being used with success as an observatory platform, in some respects investigators are still learning how to do this sophisticated research in space. Each flight helps them better understand how to design and operate instruments that are sensitive to faint emissions of radiation from deep space but are protected from similar emissions arising from the Earth and the Shuttle itself, that can hold highly accurate and stable pointing despite the Shuttle's motion, and that can be shielded from contamination and temperature extremes. They also are learning how scientists on the ground and on the Shuttle can best interact with and control these complex instruments. In response to the technical challenges of high-precision astronomy and astrophysics in the Shuttle environment, new devices and new techniques are bringing the complex universe into ever-sharper focus.

Cosmic Rays: Several cosmic ray particle detectors have flown aboard the Shuttle, the most sophisticated being the huge (2-ton) Cosmic Ray Nuclei Experiment on Spacelab 2. Although cosmic ray particles bombard Earth's upper atmosphere continuously, the flux in any one place is very low, particularly for the highest energy particles. Thus, it takes a large collector

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and a long time to "catch" enough cosmic ray particles to draw conclusions about their energy and mass. Identification of the particles and measurement of their energies pose major technical challenges.

The Spacelab 2 detector was designed to study cosmic rays with energies almost 100 times greater than those previously studied. During the mission, it recorded some 40 million events at a rate of 70 per second. Only one-tenth of 1 percent of the data, however, represents the rare ultra-high-energy cosmic rays. The large but delicate apparatus operated very well; analysis of the particle tracks through the detector is providing a mass of data about cosmic ray trajectories, charge states, and energies. This information is revealing the composition and origin of high-energy particles from other parts of the universe.

Much smaller detectors flown on other missions have had comparable success in recording lower energy particles. The highly sensitive Spacelab 3 Ions instrument detected about 20,000 cosmic ray events; the particle tracks will be painstakingly analyzed to extract information about trajectories, arrival times, and charge states. A detector on STS-3 recorded several high-speed impacts of cosmic dust particles in an investigation of the particle population in the spacecraft environment.

The value of the Shuttle/Spacelab system for these investigations is that large detectors can be flown and returned for analysis after a sufficiently long collecting period. From tell-tale tracks in the detector materials, scientists are gaining new insight into the enigmatic particles that race through space at almost the speed of light, bringing information about the violent events that produced them and the interstellar fields through which they have traveled.

X-Ray Views: The most successful astronomical observations from the Shuttle to date have been made with X-ray telescopes. These novel instruments carried on the Spacelab 1 and 2 missions performed essentially flawlessly and during many hours of operation collected many high-quality images as well as spectral data. For the most part, the instruments were used for detailed examination of known X-ray sources of various types – supernova remnants, galaxy clusters, quasars – rather than for search and discovery surveys. Scientists are pleased with the new information.

One of the most rewarding aspects of these missions was the direct operation of the telescopes by scientists on the ground at the Payload Operations Control Center. The scientists issued instrument commands, received data, and engaged in preliminary data analysis throughout the missions. This immediacy of instrument control and data collection is a new experience offered by the Shuttle/Spacelab system and is well suited to astronomical observations.

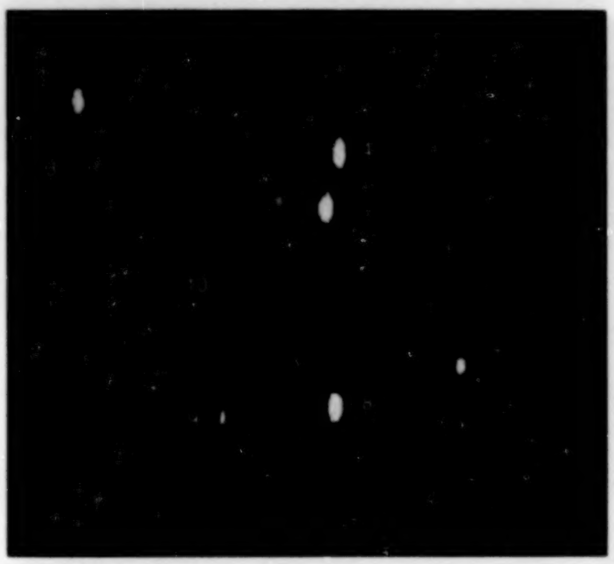
Among the most interesting Spacelab 2 results to date are the discovery of a remarkably high-energy

Scientists on the ground planned observations and controlled the operation of the X-ray telescope.

X-ray source near the center of our galaxy; discovery of a hard, extended component in the emission around the galactic center; and mapping of the Perseus cluster of galaxies four times further out radially than was previously possible, along with observations of changes in its spectrum at different positions, also observed by a Spacelab 1 instrument. The dual X-ray telescope flown on Spacelab 2 used a new technique to yield the first true two-dimensional images in high-energy X-rays. X-ray astronomy is still a relatively young discipline, but the advances in instrument sensitivity and sophistication demonstrated on Shuttle flights are accelerating its progress.

Ultraviolet Views: The Shuttle also appears to be a suitable platform for ultraviolet telescopes, such as the Far Ultraviolet Space Telescope (FAUST, Spacelab 1) and the Very Wide Field Camera (VWFC, Spacelabs 1 and 3). However, due to technical difficulties with these ultraviolet instruments, the results to date are less revealing than anticipated.

The FAUST instrument, designed to observe broad, faint sources in the 150 to 200 nanometer portion of the spectrum (far ultraviolet), operated properly, but when the photographic film was retrieved after the mission, investigators were disappointed to find



This map, made in X-rays, shows all the sources observed at length by the Spacelab 2 X-ray telescope.

1. *Perseus cluster*
2. *3C129.1*
3. *A399/401*
4. *Coma cluster*
5. *Virgo cluster*
6. *A2319*
7. *Galactic center*
8. *Centaurus*
9. *Vela supernova remnant*
10. *A754*

The combined X-ray emissions from a cluster of galaxies in Perseus span the 2.5 to 25 keV energy band. This image extends the map of the cluster four times farther than previous measurements and shows areas with higher energy X-ray flux. X-ray energy concentrations are highest at the center of the galactic cluster (white) and lowest near the fringe (pink).

Clusters of galaxies were prime targets for the X-ray telescope which studied not only the individual galaxies but also the interstellar matter and gases throughout the cluster. This visible light image shows a cluster of galaxies in Virgo.

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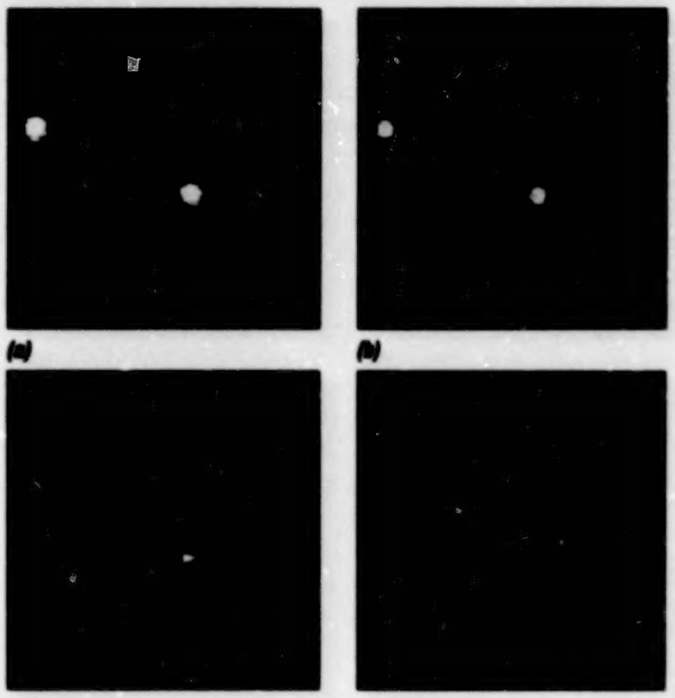
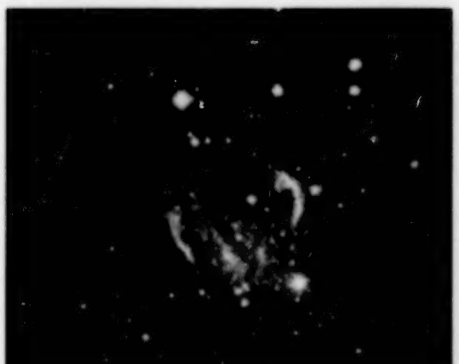
it overexposed. Only a few usable images were obtained, among them the first far ultraviolet image of the complete Cygnus Loop supernova remnant. The intense background that contaminated the film was determined to be non-astronomical, most likely caused by glowing arcs of atomic oxygen that encircle Earth at tropical latitudes.

To avoid this problem on future reflights, investigators have already modified the instrument to record photons electronically as they arrive rather than record them on film as time exposures. This electronic detector will be able to analyze the cause of the film fogging that compromised Spacelab 1 observations. Understanding the causes of background interference – whether they are natural or induced by the Shuttle – is important because future space telescopes will be viewing under similar conditions.

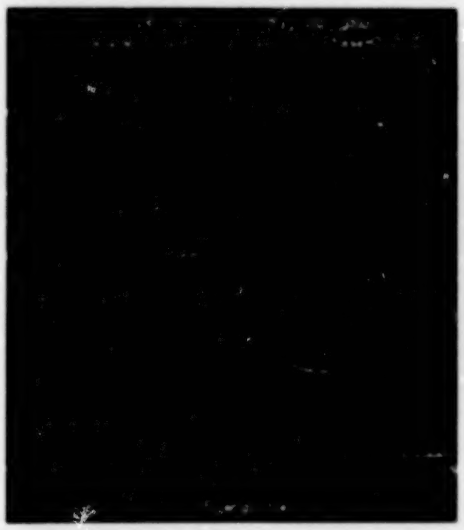
The electronic system has other advantages: it is easier to calibrate than the film system, and data are in a form that can be analyzed immediately by computer. No data will be lost because of contamination, since high radiation backgrounds can be separated. Calibration tests indicate that in 10 minutes the new FAUST can detect a 20th magnitude star and at longer exposure times will be able to detect diffuse sources as faint as 27th magnitude, the



These four maps of the galactic center in specific energy ranges show how sources may radiate at one energy level and not at all at others. For example, GX3+1 (upper left corner of photos) radiates strongly in the energy ranges from 3 to 12.5 keV (a), much less between the energies of 12.5 to 20 keV (b & c), and disappears, emitting no radiation at higher energies of 20 to 32 keV (d).



The Far Ultraviolet Space Telescope (FAUST) took this 2-minute exposure of the Cygnus Loop, a supernova remnant located about 1,500 light-years from Earth. The image yielded information on the small-scale structure of the interstellar medium around the supernova.

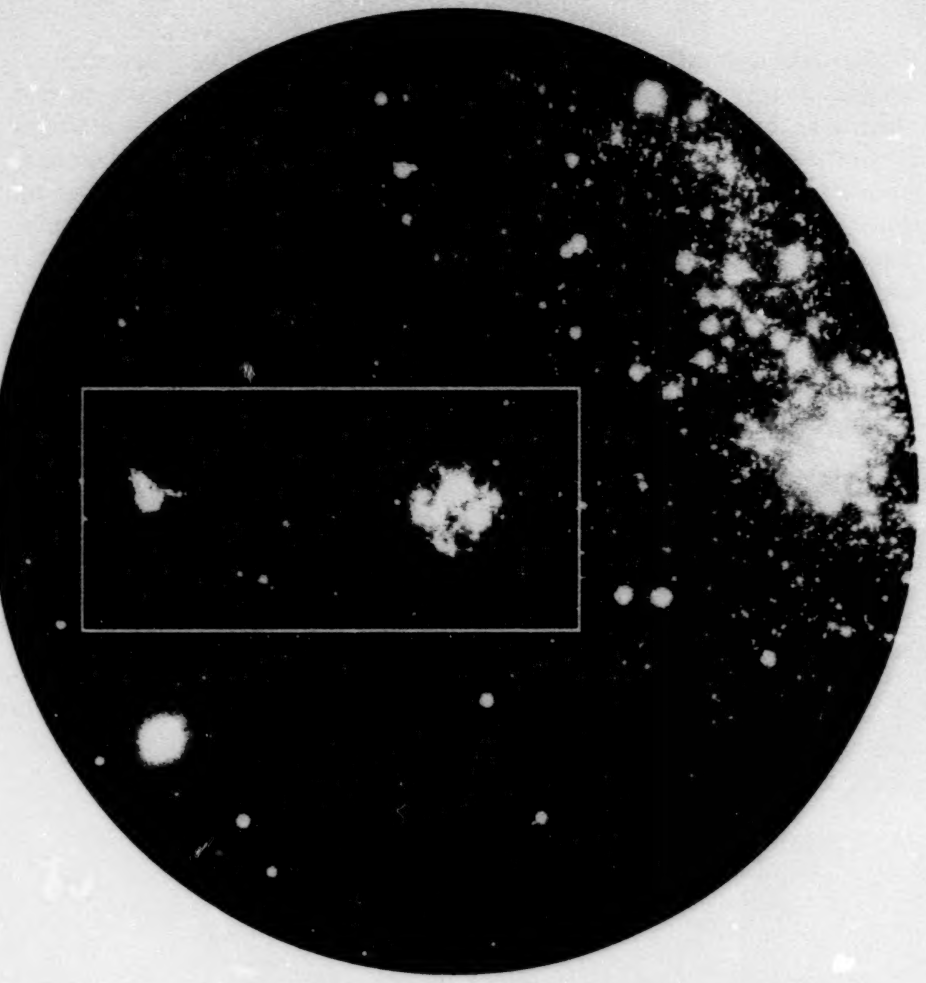


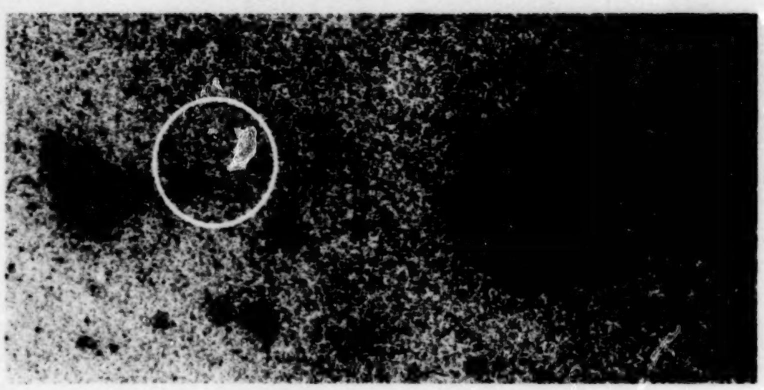
An X-ray spectrometer flown on the Spacelab 1 mission collected high-resolution spectra that provided information on the temperature, elemental abundance, and electron density in the hot plasma generally associated with cosmic X-ray sources. This spectrum of Cygnus X-3, a galactic X-ray source, reveals intensity variations with a period of 4.8 hours, implying binary motion of stars in a very compact system.

edge of sensitivity for current far ultraviolet observations.

The new detector is possible because of advances in technology since FAUST was first designed; with reflight opportunities, instruments can be upgraded as new technology becomes available. The ability to bring an instrument back after a mission and improve its performance for the next mission is a unique advantage of the Shuttle and Spacelab.

The Very Wide Field Camera has flown twice. On the Spacelab 1 mission, the camera operated properly and completed 48 exposures of 10 astronomical targets, including a superb ultraviolet image of a bridge of hot gas between the Large and Small Magellanic Clouds. These images can be used to search for new ultraviolet objects and to understand known objects better. However, the planned viewing times for the instrument were shortened as a result of the delayed launch date and shorter orbital nights, and most of the photographs suffered from a high background level of stray light from Earth's twilight/dawn horizon. About 40 percent of the planned exposures were achieved. On the Spacelab 3 mission, complications arose and no images were made.





A cloud of hot stars that forms a bridge between two galaxies was imaged by the Very Wide Field Camera. The Large Magellanic Cloud is centered in the circular image with the other galaxy (the Small Magellanic Cloud) to the left and the Milky Way on the right. The faint region within the circle in the enlargement (below) is part of the cloud of stars between the galaxies.

Infrared Views: The goals of infrared astronomy on the Shuttle are both scientific and technical—to map and measure celestial sources of infrared radiation and to evaluate infrared telescope technology in the Shuttle environment. The Infrared Astronomy Satellite (IRAS, 1983-1984) led the way for infrared telescopes, successfully mapping most of the galaxy by means of a supercold (cryogenic) detector system. Now investigators are doing the necessary follow-on studies to expand our knowledge of the infrared universe and to improve the performance of cryogenically cooled instruments.

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A small infrared telescope (IRT) carried on the Spacelab 2 mission produced mixed results, meeting more technical objectives than scientific. An infrared telescope must be cooled to keep its own thermal radiation from masking the radiation from celestial sources. Performance of the superfluid helium/porous plug cooling system exceeded expectations, demonstrating convincingly that an extremely low operating temperature (3.1 degrees Kelvin) can be established and maintained. The cryogenic system proved to be both stable and efficient, meeting all the technical requirements for scientific performance.

The astronomical results of this initial foray, however, were partially compromised by an unexpected problem. Shortly after the telescope cover was removed, the mid-wavelength detectors became saturated by an intense infrared background, making planned observations of faint celestial sources impossible in that part of the spectrum.

Despite this difficulty, the telescope successfully mapped about half of the galactic plane at shorter wavelengths than IRAS, filled a 5-degree gap in IRAS data, and covered another region not in a standard sky survey. Scientists also investigated the origin and nature of the surprising infrared background. The investigation yielded useful information about the infrared environment of the Shuttle; however, the prime candidate explanation, based on a real-time video survey and postflight examination of the telescope, is that damage to the light shield caused some of the high background level. More was learned about the Shuttle environment by the IRT in a series of co-observations with other instruments to determine whether the Shuttle glow phenomenon or experimental electron beam firings would interfere with infrared astronomical viewing. These experiments indicated no apparent infrared effect of the visible Shuttle glow.

Observatories in Space: The nation's strategy for astronomy and astrophysics over the next few decades is a multi-spectral exploration of the universe. This campaign to observe the universe as it appears in each region of the electromagnetic spectrum requires diverse instruments and spacecraft, ranging from small rocket-borne detectors to large observatory platforms orbiting near the Space Station. The Shuttle and Spacelab will play a significant role in bringing this strategy to fruition.

NASA is developing a major free-flying observatory for each portion of the spectrum, from infrared through gamma rays. The first to be deployed is the Hubble Space Telescope for astronomy in the visible spectrum, to be followed shortly by the Gamma Ray Observatory and eventually the Advanced X-Ray Astrophysics Facility and the Space Infrared Telescope Facility. Each of these is designed to be

Spacelab 2 investigators keep watch during Infrared Telescope operations.

launched and serviced in the Space Shuttle and to have an orbital life of many years. The Shuttle is also important as an assembly and deployment site for ambitious future systems of antennas, such as the Large Deployable Reflector, an infrared observatory. Scientists welcome these new opportunities for prolonged observations from space.

Besides serving as the launch vehicle and service center for the large observatories, the Shuttle will serve as host carrier for smaller instruments in complementary observations. Two series of Spacelab missions dedicated to astronomy and astrophysics are planned: the Astro missions for ultraviolet and X-ray observations and the Shuttle High Energy Astrophysics Laboratory (SHEAL) missions for X-ray observations. Each mission carries compatible instruments that can operate independently or in concert for detailed studies of the same celestial objects that will be scrutinized by the large observatories. These Shuttle-borne instruments make important observations that help to define and corroborate the viewing programs of the large observatories. They also have the virtue of being returned, modified, and reflown in response to discoveries and changing research goals.

Within the disciplines of astronomy and astrophysics, the use of the Shuttle/Spacelab as a manned observatory platform is a prelude to the Space Station era, when attached or co-orbiting platforms become available for observations of longer duration. Even then, Shuttle flights will remain important for proof-testing of new instrument concepts as technology advances. The Shuttle and Spacelab are necessary elements in the broad strategy to chart the universe on all scales, at all wavelengths. ■

In this infrared map of the galactic center, the colors represent different intensities of surface brightness. The map made at short wavelengths (2 microns) will augment Infrared Astronomical Satellite (IRAS) data.

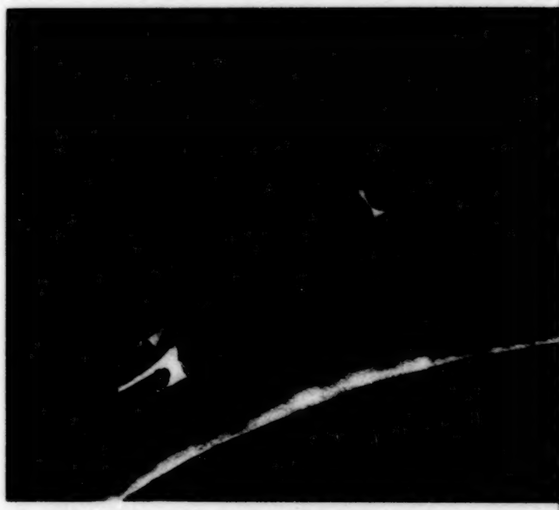
This infrared image, also made at 2 microns, shows how surface brightness varies at the center of the galaxy.

Below: Instruments carried on the Shuttle make observations that complement observations by the Hubble Space Telescope and other large astronomical observatories.

Astronomy and Astrophysics Investigations

OSS-1/STS-3	*Microabrasion Foil Experiment* *J.A.M. McConnell, University of Kent, United Kingdom*
Spacelab 1/STS-9	*Far Ultraviolet Space Telescope (FAUST)* *C.S. Bowyer, University of California, Berkeley, California*
	Isotope Stack *R. Beaujean, Kiel University, Germany*
	Spectroscopy in X-Ray Astronomy *R.D. Andresen, European Space Research & Technology Center* *Noordwijk, The Netherlands*
	Very Wide Field Camera *G. Courtés, Space Astronomy Laboratory, Marseilles, France*
Spacelab 3/51-B	*Studies of the Ionization of Solar and* *Galactic Cosmic Ray Heavy Nuclei (Ions or Anuradha)* *S. Biswas, Tata Institute of Fundamental Research, Bombay, India*
	*Very Wide Field Camera** *G. Courtés, Space Astronomy Laboratory, Marseilles, France*
Spacelab 2/51-F	*Cosmic Ray Nuclei Experiment* *P. Meyer and D. Müller, University of Chicago, Illinois*
	Hard X-Ray Imaging of Clusters of Galaxies - X-Ray Telescope (XRT) *A.P. Willmore, University of Birmingham, United Kingdom*
	Small Helium-Cooled Infrared Telescope (IRT) *G.G. Fazio, Smithsonian Astrophysical Observatory* *Cambridge, Massachusetts*
Spartan 1/51-G	*X-Ray Imaging of the Galactic Center & Extended Sources* *G. Fritz, Naval Research Laboratory, Washington, D.C.*

**Reflights*



The Astro telescopes will survey the sky, studying the signatures of stars, galaxies, quasars, planets, and comets.

Chapter 9

Testing New Technology

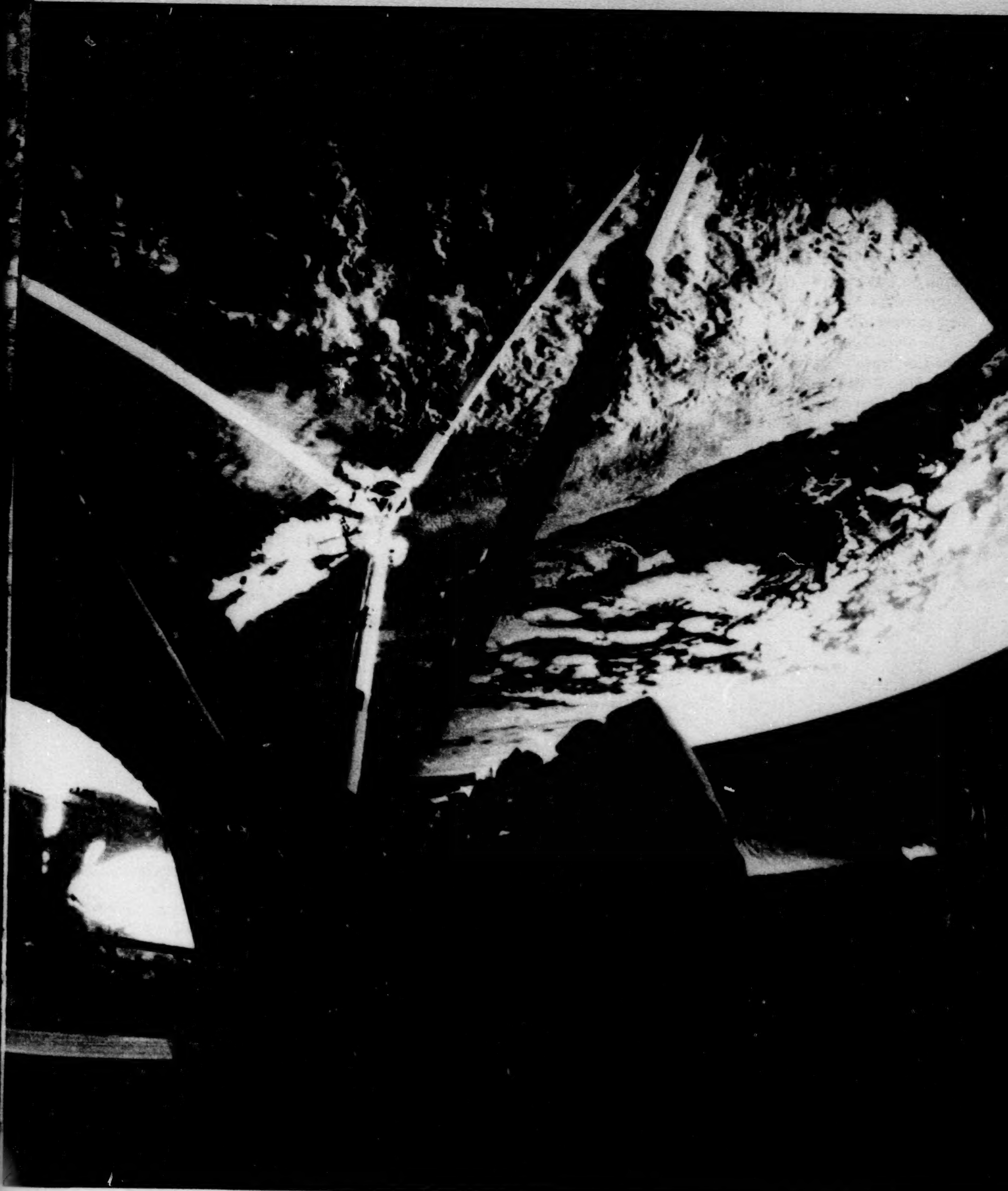
Future space missions require technologies not yet in use for the design of scientific facilities that will be larger or longer lived than anything yet flown. Spacelab and Shuttle missions add to the tools and experience that space designers may use with confidence. Thus far, several orbital tests of new technology have been performed. These technologies may shape the future of science in space.

Ambitious projects that are too large to be launched as a unit by the Space Shuttle, like the 20-meter (66-foot) wide Large Deployable Reflector for infrared astronomy, will be assembled by astronauts. Understanding of the time and effort for that and similar projects will come from experiments such as the Experimental Assembly of Structures in EVA and the Assembly Concept for Construction of Erectable Space Structure (EASE/ACCESS, 61-B). Two astronauts repeatedly assembled and disassembled two simple structures, a tetrahedron and a triangular column, to measure how quickly they would become proficient or fatigued. By all measures, the work was performed efficiently, despite the unusual size of the structures and the repetitive nature of the tasks.

The weightless behavior of many mechanisms is not well understood. The Solar Array Flight Experiment (OAST-1) tested a full-scale model, 3.9 meters (12.7 feet) wide and 31.5 meters (103.3 feet) long, of a candidate design for a lightweight solar array and a new measurement technique for monitoring the characteristics of the device in space. While the wing itself proved to be very stiff, many of its motions while extended and during retraction were unexpected. It also showed a surprising tendency to bow at night into the shape of an airfoil. This information is valuable input to the engineering and design process for observatory-class spacecraft that depend upon solar arrays for power.

The orbital refueling experiment on the 41-G mission demonstrated the ability to refuel satellites in space when their self-contained thruster systems have depleted fuel reserves. Refueling equipment was connected to a simulated satellite hookup, and hydrazine, a very toxic and corrosive fluid, was transferred between the two tanks. This demonstration is a precursor to actual Shuttle refueling missions for satellites.

Even mundane objects such as pump bearings must be reconsidered in space. All our knowledge of bearings comes from experience on Earth where gravity pulls the lubricant to the bottom of the bearing case, forming a liquid-gas film that supports the shaft. Transparent plastic models of three types of bearings were photographed in the bearing lubrication experiment on Spacelab 1 to examine how this phenomenon changes in microgravity.



The thermal canister experiment (OSS-1) demonstrated heat pipes that control temperature by boiling and condensing ammonia within a closed circuit. These worked better in space than in ground tests, and a similar device was approved for use on the electronics module of the Astro astronomy payload.

The Superfluid Helium Experiment (Spacelab 2) was significant for fluid physics (understanding the properties of this peculiar substance) and also for technology (evaluating its behavior in microgravity and demonstrating a cooling system and containment vessel). The coldest liquid known, superfluid helium is a promising cryogen for detectors that must be maintained at extremely low temperatures for best performance; effective new cryogenic systems are required for more than one space telescope now under consideration. This experiment examined temperature variations and slosh patterns in the container for information relevant to the design of superfluid helium dewars and also evaluated the temperature control system. Early results indicate that superfluid helium can be managed efficiently in space with the porous plug cryostat; data from this investigation will influence not only the science of fluid physics but also the design of new instruments for research in space.

All spacecraft alter the space environment by their presence. Gases and particles escape from the spacecraft material, and various kinds of exhaust and waste are released by the vehicle's power and propulsion systems. These contaminants may compromise data collection and instrument performance.

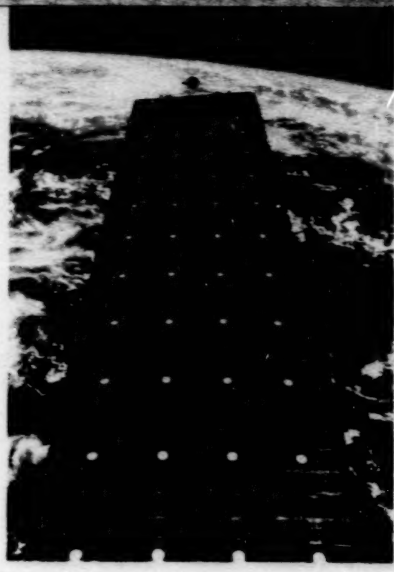
To understand the Space Shuttle's effects, an Induced Environment Contamination Monitor (IECM) was flown on three of the early orbital flight tests and on Spacelab 1; smaller contamination experiments have been carried out by instruments on these and other missions. The Shuttle orbiter's impact on the environment was found to be within expectations or controllable, for example, by installing a new payload bay liner to eliminate a dust problem.

Two phenomena were discovered (without the IECM) that are common to all spacecraft and weaken markedly with greater altitude. One is Shuttle glow, a dim, diffuse glow that is strongest in the visible red and near-infrared parts of the spectrum. This was detected during low-light photography of a plasma physics experiment on STS-3 and raised concern that it might interfere with scientific observations. It was also studied by the Infrared Telescope on Spacelab 2, which viewed the region near the Plasma Diagnostics Package while it was being exposed to oncoming plasma around the Shuttle. Its cause is still being investigated, but Atmospheric Explorer data indicate that the glow is not unique to the Shuttle.

Astronauts built the EASE and ACCESS structures in the Shuttle payload bay in experiments to determine how efficiently humans can do orbital construction.

The other discovery is that atomic oxygen, freed when sunlight splits oxygen molecules, recombines with some spacecraft coatings. This was first noticed on television camera coverings after STS-3. A similar effect had been seen on Skylab's sunshade after half a year of exposure, but since no samples were returned for analysis, the cause was only hypothesized.

The research agenda for the near future includes further tests of cryogenic systems and assembly of large structures, elements that are crucial to the Space Station and large orbital observatories. Although the goal of technology experiments in space is to resolve engineering issues, their potential scientific benefit cannot be ignored. Improved understanding of the behavior of materials or the performance of new technology in microgravity may be applied to the design of advanced scientific instruments. Technological breakthroughs usually lead to scientific progress as well. ■



A 31.5-meter (103.3-foot) long solar array was deployed from the Shuttle to study the motions of large structures in space. Similar arrays will be used on the Space Station and large observatory spacecraft.

Space Technology Investigations

OSTA-1/STS-2 **OSS-1/STS-3** **STS-4** **Spacelab 1/STS-9**	*Induced Environment Contamination Monitor** *E. Miller, NASA Marshall Space Flight Center* *Huntsville, Alabama*
OSS-1/STS-3	*Characteristics of Shuttle/Spacelab Induced Atmosphere* *J.L. Weinberg, University of Florida* *Gainesville, Florida*
	Contamination Monitor *J.J. Triolo, NASA Goddard Space Flight Center* *Greenbelt, Maryland*
	Thermal Canister Experiment *S. Ollendorf, NASA Goddard Space Flight Center* *Greenbelt, Maryland*
Spacelab 1/STS-9	*Bearing Lubricant Wetting, Spreading & Characteristics* *C.H.T. Pan, Columbia University, New York, New York* *A. Whitaker, NASA Marshall Space Flight Center* *Huntsville, Alabama*
OAST-1/41-D	*Solar Array Flight Experiment* *L.E. Young, NASA Marshall Space Flight Center* *Huntsville, Alabama*
	Solar Cell Calibration Facility *R.G. Downing, NASA Jet Propulsion Laboratory* *Pasadena, California*
OSTA-3/41-G	*Orbital Refueling System Experiment* *W. Huffstetler, NASA Johnson Space Center* *Houston, Texas*
Spacelab 2/51-F	*Properties of Superfluid Helium in Zero-Gravity* *P.L. Mason, NASA Jet Propulsion Laboratory* *Pasadena, California*
HH-G1/61-C	*Particle Analysis Camera, Capillary Pump Loop, and Mirror Contamination* *T. Goldsmith, NASA Goddard Space Flight Center* *Greenbelt, Maryland*
61-B	*Assembly Concept for Construction of Erectable Space Structure (ACCESS)* *W.L. Heard, Jr., NASA Langley Research Center* *Hampton, Virginia*
	Experimental Assembly of Structures in EVA (EASE) *D.L. Akin, Massachusetts Institute of Technology* *Cambridge, Massachusetts*

The Induced Environment Contamination Monitor characterized the Shuttle environment during spaceflight; resultant data may affect experiment designs.

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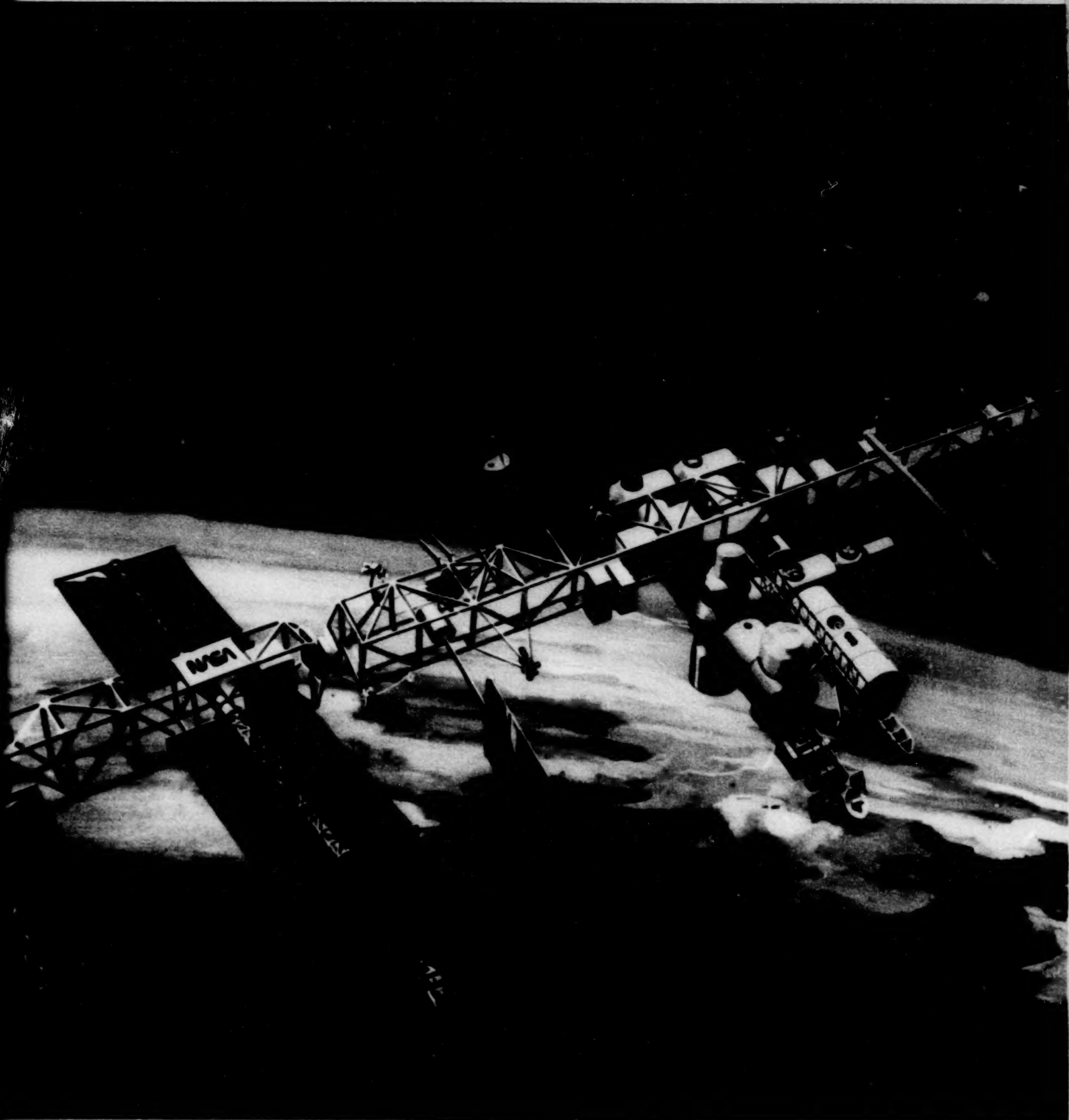

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Chapter 10

Future Research aboard the Shuttle/Spacelab

The record of achievements during the first 5 years of scientific activity aboard the Shuttle/Spacelab is remarkable. Reams of data, scores of samples, and dozens of discoveries are the fruits of exploratory investigations in these versatile facilities. Scientists will be occupied for years analyzing and interpreting the vast amount of new information gained during these forays into space and planning the follow-up studies. The Shuttle and Spacelab are demonstrably successful research facilities for disciplines as different in aims and techniques as life sciences and astronomy, materials science and Earth observations. Scientists working in these fields, as well as solar-terrestrial physics, fluid physics, and behavioral science, have found the Shuttle/Spacelab to be a hospitable, productive environment for pioneering research.

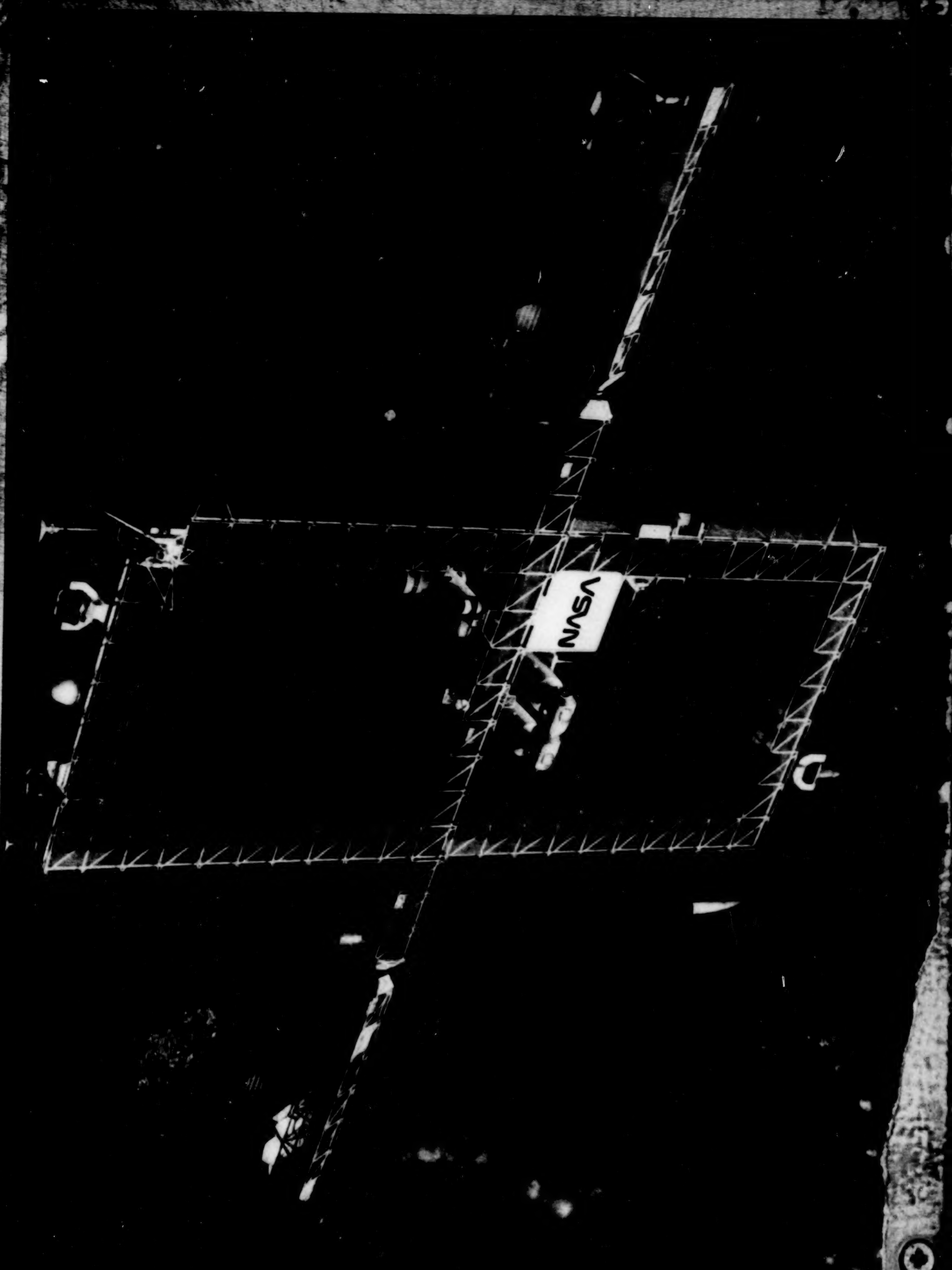
Despite these successes, the first missions have only begun to demonstrate the science potential of the Shuttle/Spacelab. We have not yet begun to exhaust the capabilities of the instruments for doing research in space. In many cases, the first round of investigations opened our eyes to new lines of inquiry, unexpected results, and intriguing problems that require further experiments and observations.

The impressive inventory of instruments and facilities flown to date remains available for reflight and refurbishment to carry on the investigations already initiated. Promising experiments in every science discipline are being pursued, and lessons learned on previous missions are being applied in planning future missions on the Shuttle and the Space Station.

For concentrated research programs, NASA is developing complementary instrument groups that will fly on missions devoted to a single science discipline. The trend of future missions will be dedicated observatories and laboratories rather than multidisciplinary payloads. Series of dedicated missions already on the Shuttle schedule include the Spacelab Life Sciences laboratory, Materials Science Laboratory, International Microgravity Laboratory, Spacelab J, Space Plasma Laboratory, Atmospheric Laboratory for Applications and Science, Shuttle Radar Laboratory, Astro, and the Shuttle High Energy Astrophysics Laboratory. Each of these specialized facilities has evolved from the first generation of Shuttle/Spacelab flights. Instruments are being modified, procedures refined, and objectives focused in response to the results obtained during previous missions.

This evolution will continue into the Space Station era, when instruments originally developed for Shuttle/Spacelab missions will be adapted for permanent operation on the manned Station or its companion platforms. Shuttle/Spacelab missions have

Shuttle/Spacelab experiments are models for Space Station investigations, and much of the Space Station's research hardware will be demonstrated aboard the Shuttle.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provided not only the opportunity for immediate science but also the testbed for instruments and research concepts to be incorporated in the Space Station several years hence.

Some Spacelab investigations will lead to more intense investigations for longer periods aboard the Space Station. Although the scientific payload complement is not yet selected, it is expected that Spacelab experiment facilities will be adapted to the Space Station or serve as models for new apparatus. The laboratory module, for example, may include materials and life science facilities first flown aboard Spacelab. The Spacelab solar and astronomical telescopes may form a core observatory that can be mounted on the Space Station or a co-orbiting platform. Instruments that scan the Earth's surface and atmosphere will be combined to form the Earth Observation System (EOS), mounted on unmanned platforms in polar orbits, to make detailed observations based on the results from Spacelab missions. Plasma physics instruments and the Tethered Satellite System will form the nucleus of a Solar-Terrestrial Observatory manned module and polar platform to define how the sun and space affect our environment.

Rarely is a theory confirmed or rejected by a single observation or experiment; rather, theories and models are successively refined through a course of investigations. The Shuttle and Spacelab make such a series of investigations possible through repeated reflights and evolution of the instruments or techniques. Thus, if a first flight is not as successful as hoped or if the outcome is different than expected, scientists have the opportunity to try again or reverify unusual results. This ability to build on experience and improve investigations is directly analogous to the incremental progress of science in laboratories and observatories on the ground.

With Spacelab, we are extending our knowledge in the space sciences and learning the best ways to formulate investigations. Continued Shuttle missions spanning the development of the Space Station, and even complementing the Station as it matures, will assure the nation of a vigorous space science program as we move into the next century.

Curiosity led us into space and continues to be the impetus for space science. The Shuttle and Spacelab are well suited to satisfy the urge for discovery and knowledge. ■

Shuttle/Spacelab research has stimulated new questions, revealing gaps in knowledge that reach across all scientific disciplines. To resolve these questions and others certain to arise from future investigations, the Space Station will evolve and new observatories and platforms will join the fleet of research spacecraft.

Acknowledgments

Authors and Editors:	Valerie Neal, Tracy McMahan, and Dave Dooling, all of Essex Corporation
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